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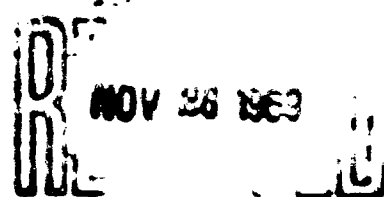
### PULSE TRANSMISSIONS AT VHF IN A TROPICAL RAIN FOREST

Semiannual Report No. 11

Prepared by  
John J. Hicks  
Richard G. Robertson

Submitted to  
U. S. ARMY ELECTRONICS COMMAND  
Fort Monmouth, New Jersey

Contract No.  
DA 36-039 SC-90889



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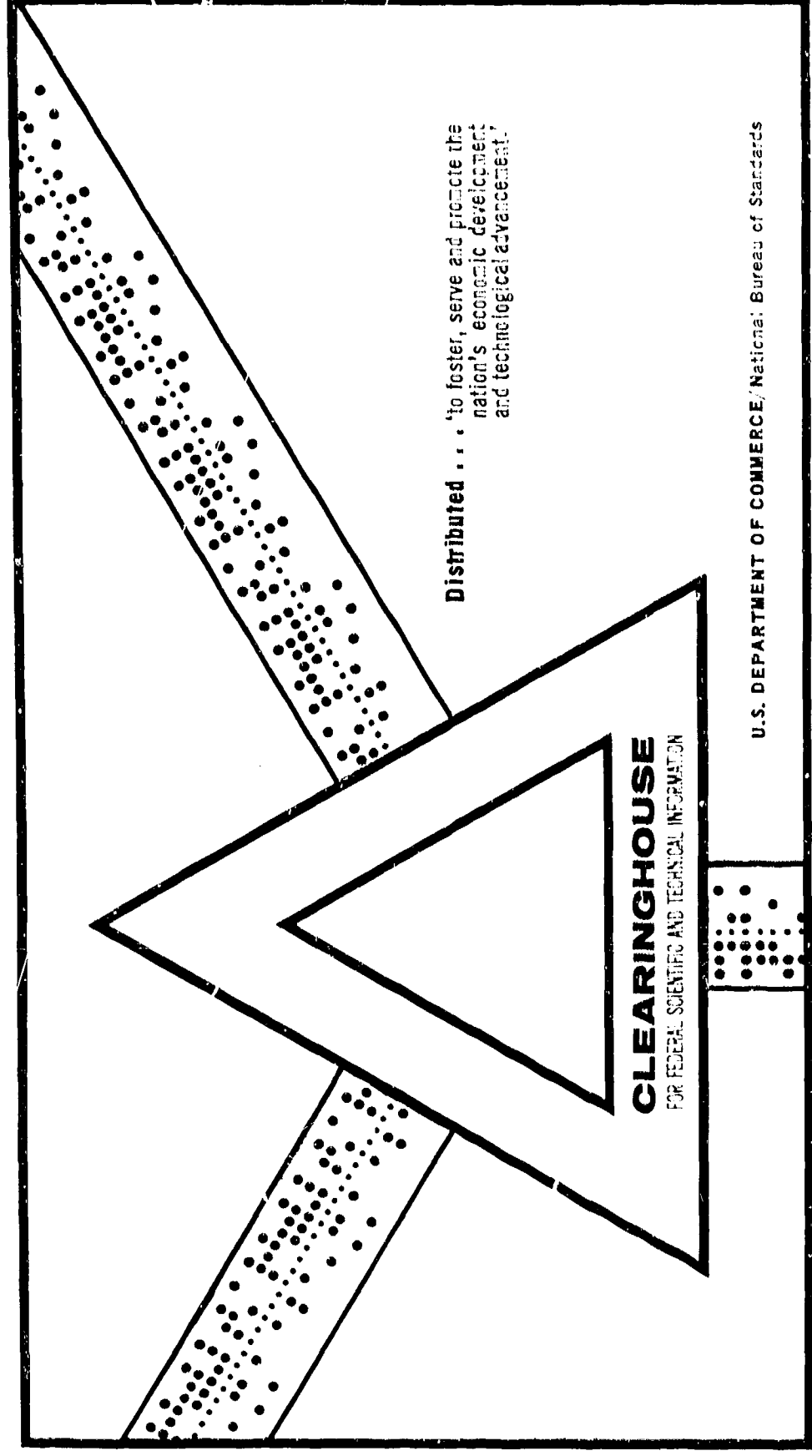
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John J. Hicks, et al

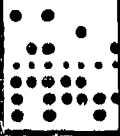
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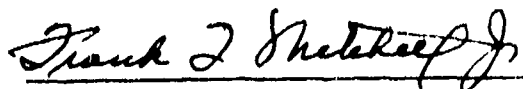
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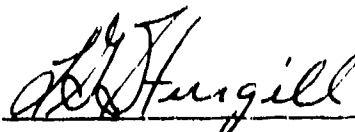
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## SUMMARY

This semiannual report is ~~one of a series~~ presenting results from experimental and analytical investigation of the propagation of radio waves in tropical jungle environments. The experimental work has been done in a tropical rain forest test area in Southern Thailand. The objective of this program is to obtain and analyze information that is generally applicable to improving the development, design, and operation of short range communications systems for tropical jungle environments.

The work covered by this report is especially concerned with the propagation of pulsed, or digital, signals in such an environment. Transmitted pulses of about 1  $\mu$  sec were received by fixed and mobile receiving systems. Distortion in the pulse amplitude and frequency spectra was measured at carrier frequencies of 50, 100 and 150 MHz. The results of these measurements indicate clearly that the rain forest jungle creates a frequency-selective propagation channel and, with wind-driven tree motion, a time-selective channel as well. The measurements imply a coherent bandwidth of about one MHz for this type of jungle channel.

From the data obtained thus far a preliminary model has been constructed, based on multiple scattering from the dominant tree, which qualitatively explains the observed data.

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## CONTENTS

	<u>Page</u>
ACKNOWLEDGMENT.....	i
SUMMARY .....	iii
LIST OF FIGURES.....	vii
LIST OF TABLES.....	x
1. INTRODUCTION.....	1
2. EQUIPMENT AND CALIBRATION PROCEDURES.....	3
3. EXPERIMENTAL ENVIRONMENT .....	8
4. PRESENTATION OF DATA AND ANALYSIS.....	16
4.1 Mobile Pulse Measurements.....	16
4.1.1 Preliminary Measurements.....	17
4.1.2 Distortion Measurements.....	21
4.1.3 Pulse Length Measurements.....	32
4.2 Localized Pulse Measurements.....	35
4.2.1 Regions of Severe Distortion.....	36
4.2.2 Pulse Measurements in Forest Compared to Clearing.....	41
4.2.3 Pulse Measurements Near a Hilltop and the Base of a Hill.....	45
5. PRELIMINARY SCATTER MODEL.....	48
6. CONCLUSIONS.....	56
BIBLIOGRAPHY.....	58
APPENDIX A.....	60
APPENDIX B.....	64
Distribution List	

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## LIST OF FIGURES

		<u>Page</u>
2.1	Block Diagram - Pulse Transmitter.....	4
2.2	Block Diagram - Pulse Receiver.....	5
2.3	Rolligon Tractor-Trailer and Equipment in Trailer...	7
3.1	Locations of Thailand Test Areas.....	9
3.2	J & B Base Camp and Air Strip.....	10
3.3	Area II Test Site Main Access Trail.....	11
	(a) Plain View	
	(b) Elevation Profile	
3.4	Measurement Areas at a Hill, Area II Test Site.....	14
3.5	Terrain and Tree Profiles Along Main Access Trail...	15
4.1	Basic Transmission Loss - Distance.....	19
4.2	Pulse Peak Variation - Distance.....	20
4.3a	Reference Waveform at 150 MHz, Vertical Polarization, Transmitting and Receiving Antenna Heights of 13 feet, and Range of 50 feet.....	23
4.3b	Distorted Waveform (designated moderate distortion) at 150 MHz, Vertical Polarization, Transmitting and Receiving Antenna Heights of 120 and 6 feet, respectively, and Range of 1900 feet....	23
4.4a	Reference Waveform at 150 MHz, Horizontal Polarization, Transmitting and Receiving Antenna Heights of 13 feet, and Range of 50 feet.....	24
4.4b	Distorted Waveform (designated severe distortion) at Range of 1900 feet. Other conditions of transmission as in a, above.....	24
4.5	Number of (a) Severe and (b) Moderate Distortions as a Function of Frequency, Transmitting (Tx) Antenna Height, and Polarization. Frequency in MHz and polarization are identified by numbers and letters by curves.....	28

## LIST OF FIGURES (continued)

		<u>Page</u>
4.6	Number of Severe Distortions, normalized to 50 MHz. (Nomenclature same as in Figure 4.5).....	30
4.7	Location and Percent of Regions of Distortion Along Main Access Trail as a Function of Terrain, Frequency, and Transmitting Antenna Height for Horizontal Polarization.....	31
4.8a	Reference Waveform at 100 MHz, Vertical Polarization, Transmitting and Receiving Antenna Heights of 40 and 10 feet, respectively, and Range of 1600 feet.....	34
4.8b	Distorted Waveform of transmitted pulse much longer than multipath delay at above conditions of transmission. This photo is of a 4 $\mu$ s pulse. The delay is measured by the duration of distortion of the leading edge, in this case about 0.5 $\mu$ s.....	34
4.9a	Relatively Undistorted Waveform at 50 MHz, Vertical Polarization, Transmitting and Receiving Antenna Heights of 40 feet and 6 feet, respectively, and Range of 3300 feet.....	38
4.9b	Distorted Waveform of pulse transmitted as above, but received at the location of a CW minimum at 3300 foot Range.....	38
4.10a	Spectrum centered on 50 MHz, Vertical Polarization, Transmitting and Receiving Antenna Heights of 40 and 6 feet, respectively, and Range of 3300 feet.....	39
4.10b	Spectrum of Transmission like above, but received at location of CW minimum.....	39
5.1	Sketch of Ray Paths in Scatter Model.....	49
A-1	Theoretical examples of resultant waveforms for interference between two rf pulses of equal amplitude, fixed relative delay, and various relative carrier phases.....	61

## LIST OF FIGURES (continued)

	<u>Page</u>
A-2 Theoretical examples of resultant waveforms for interference between two rf pulses of different amplitude, fixed relative delay, and various relative carrier phases.....	63
B-1 Sketch of ray paths depicting scatter and interference.....	65
B-2 Sketch of Equation B-3.....	67

## LIST OF TABLES

		<u>Page</u>
3.1	Main Access Trail Markers - Ranges and elevations referenced to transmitter (Tx).....	13
4.1	Number of occurrences of distorted pulses observed along main access trail between 1000 and 5000 feet from transmitter with receive antenna height of 13 feet.....	27
4.2	Multipath Time Spread.....	35
4.3	Degree of distortion obtained with different transmitting antenna heights, $H_T$ , receiving antenna heights, $H_R$ , frequencies, and polarization. S denotes severe, M, moderate, and N, little or no, distortion. W means signal too weak to determine distortion, and a blank, no measurement. Frequency and polarization are shown above each block.....	42
4.4	Peak pulse amplitudes in clearing, minus peak pulse amplitudes in forest, in db, for different transmitting antenna heights, $H_T$ , receiving antenna heights, $H_R$ , polarization, and frequency. Blanks mean no data were obtained. Frequency and polarization are shown above each block.....	44
4.5	Peak pulse amplitudes on a hill, minus peak pulse amplitudes at the base of the hill, in db, for different antenna heights, frequencies, and polarizations. Explanation of data is the same as for Table 4.4.....	47

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## 1. INTRODUCTION

This semiannual report is one of a series on the subject of short range radio communications in tropical jungle environments. The experimental and analytical work has been done under a contract with the U. S. Army Electronics Command, Fort Monmouth, New Jersey, which has been sponsored by the Advanced Research Projects Agency of the Department of Defense. The experimental measurements have been conducted in a tropical rain forest test area in Southern Thailand, followed by analysis of the data at the company's laboratories in the United States. For convenience, the tropical rain forest test area in Southern Thailand is referred to as the Area 11 test site.

The over-all objective of this program is to collect and analyze information which is generally applicable to improving the development, design, and operation of short range communications systems for tropical jungle environments and, through these reports, to disseminate this information widely to government and industrial laboratories having need for it.

This report is concerned with the results from a preliminary series of measurements, using pulse, or digital, transmissions, to qualitatively examine the distortions introduced by the jungle vegetation through multipath phenomena.

The phenomena of short spatial fading experimentally observed in forested environments [Jansky & Bailey, 1966, and others] suggest that such environments are multipath channels at HF and above. It is well known that multipath channels place restrictions upon the design and operation of communications systems, especially digital or wideband systems, utilizing the channels [Schwartz et al., 1966]. There are however, very

limited data available to assess the multipath effects of a forested environment upon such systems. Thus, due to increased use of digital systems and the need to predict communication performance in tropical environments, an experimental program was initiated in the summer of 1968 to investigate multipath effects in a dense tropical rain forest in Thailand. The first, or exploratory, phase of the investigations, limited primarily to transmission of pulse modulated VHF carrier frequencies, was to provide estimates of the general multipath effects. This report presents the results of this phase of the investigations.

Measurements were made at carrier frequencies of 50, 100, and 150 MHz with both antennas stationary and with the receiving antenna mobile. Distortions to the pulse amplitude and spectrum and pulse lengthening are examined for various combinations of antenna heights, vertical and horizontal polarizations, three VHF carrier frequencies and different environments. The results, generally qualitative, are consistent and provide considerable insight into the properties of multipaths in the forested environment at VHF.

Presented first are discussions of the measurement equipment and the environmental test area. The several kinds of measurement procedures are described, and samples of distorted pulses are illustrated. Following an analysis of the data, a basic propagation model for a forested environment is described. Finally, the conclusions of this preliminary pulse measurement study are listed.

## 2. EQUIPMENT AND CALIBRATION PROCEDURES

A block diagram of the transmitting and receiving equipment is shown in Figures 2.1 and 2.2, respectively.

The pulse transmitter was a standard TRC/24 FM transmitter modified to operate either in a pulse or CW mode. The pulse generator provided nearly square pulses, 1 to 6  $\mu$  sec duration, which were amplified and transmitted at a repetition rate of 10 kHz. The rise and fall times for the transmitted pulses were 150 to 200 ns, and the pulse amplitude ripple was less than 1 db. The PRD frequency meter provided a monitor for the carrier frequency. The directional coupler in the output transmission line provided an attenuated sample of the signal. In the case of 100 and 150 MHz, the sample signal was detected, and its envelope displayed on the calibrated graticule of the HP 175A oscilloscope. However, in the case of 50 MHz, the detectors were unsatisfactory due to rf feedthrough, and the undetected 50 MHz pulses were displayed directly on the oscilloscope. These wave-shapes, which were recorded on the x-y plotter, gave a measure of the peak power of the pulses at the transmitter.

The peak power output of the transmitter was approximately 160 watts. After subtracting the cable loss to the antenna, the actual transmitted peak power was reduced to less than 65 watts, depending on the carrier frequency.

The pulse receiver system utilized an ACL receiver with continuously tunable plug-in heads and a passband of at least 4 MHz. The received signal, after passing through the ACL receiver, was available either at the IF frequency (31.4 MHz) or as a detected video pulse. The video signal was displayed on the HP 175A oscilloscope and, during most of the

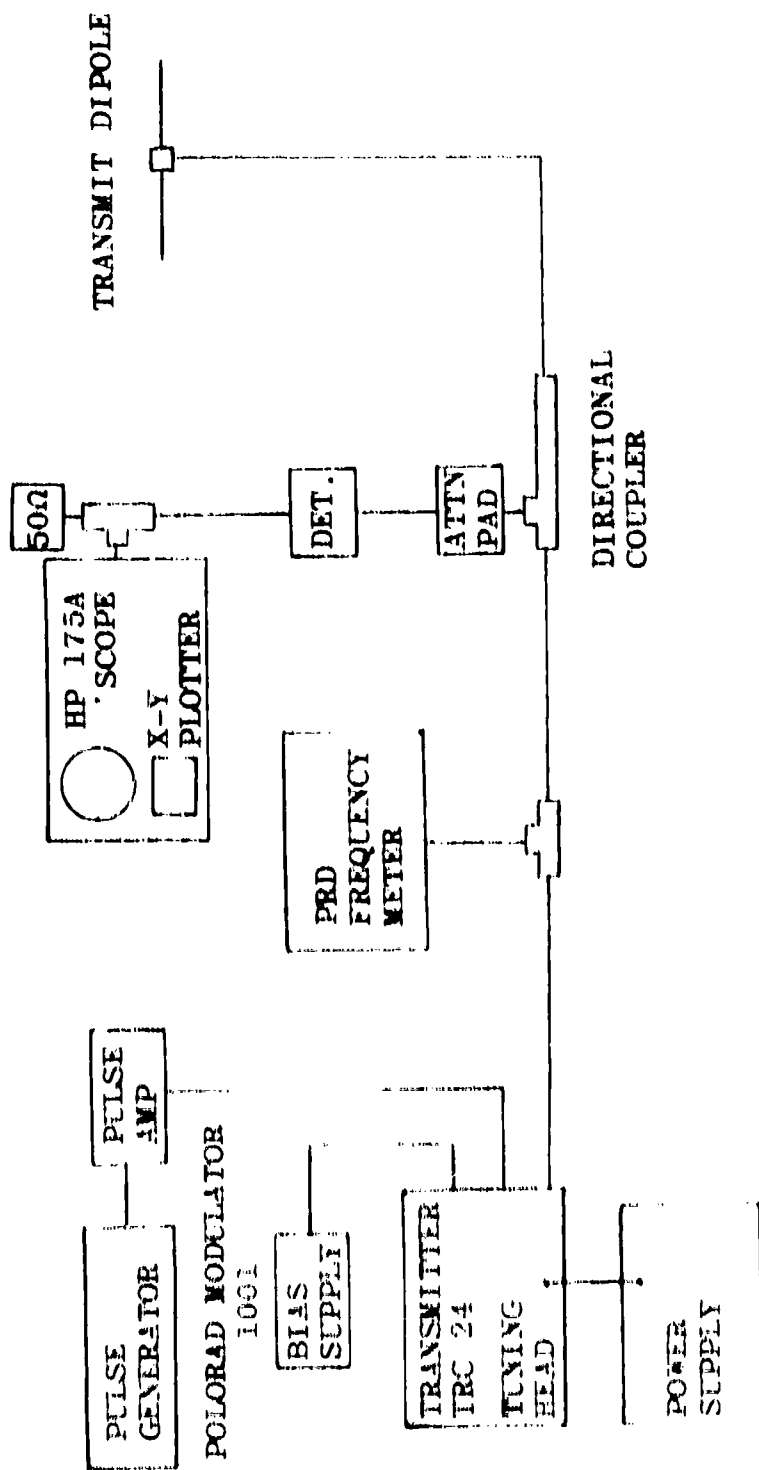


Figure 2.1 BLOCK DIAGRAM - PULSE TRANSMITTER

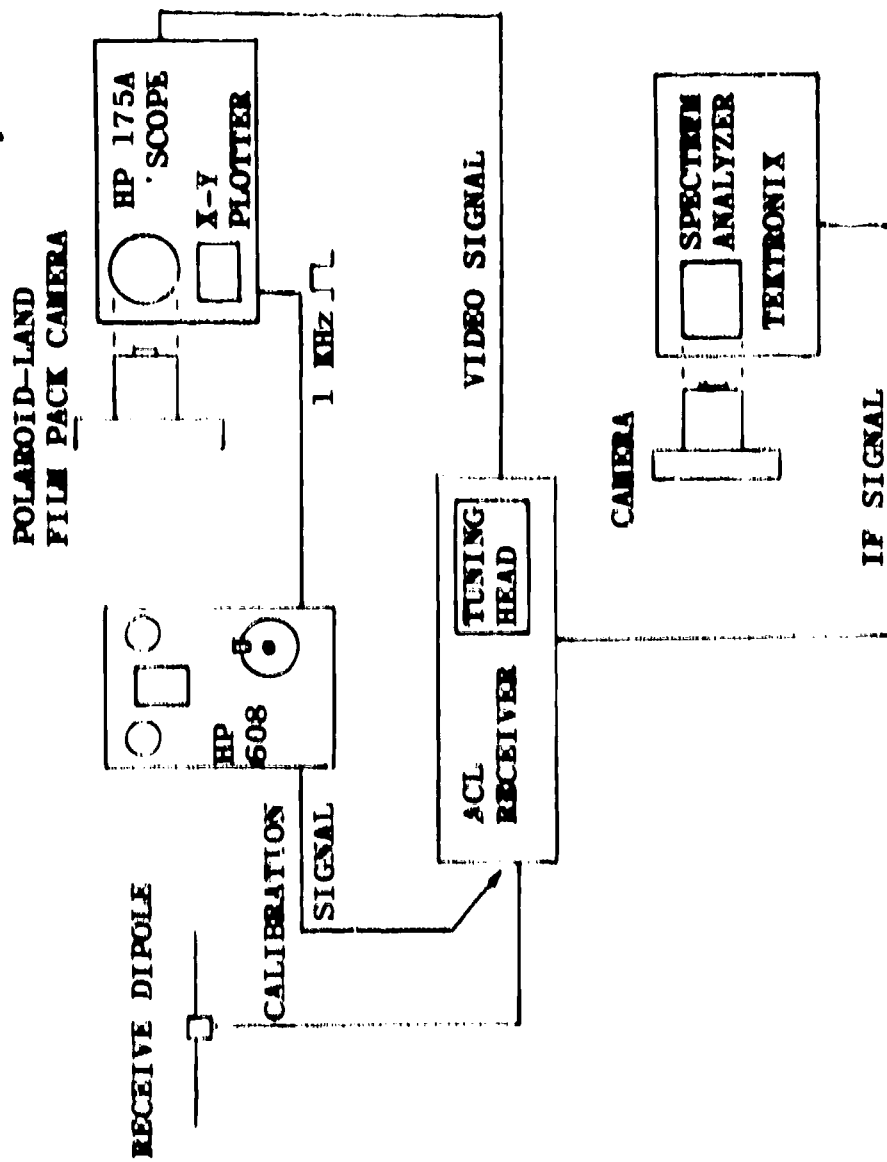


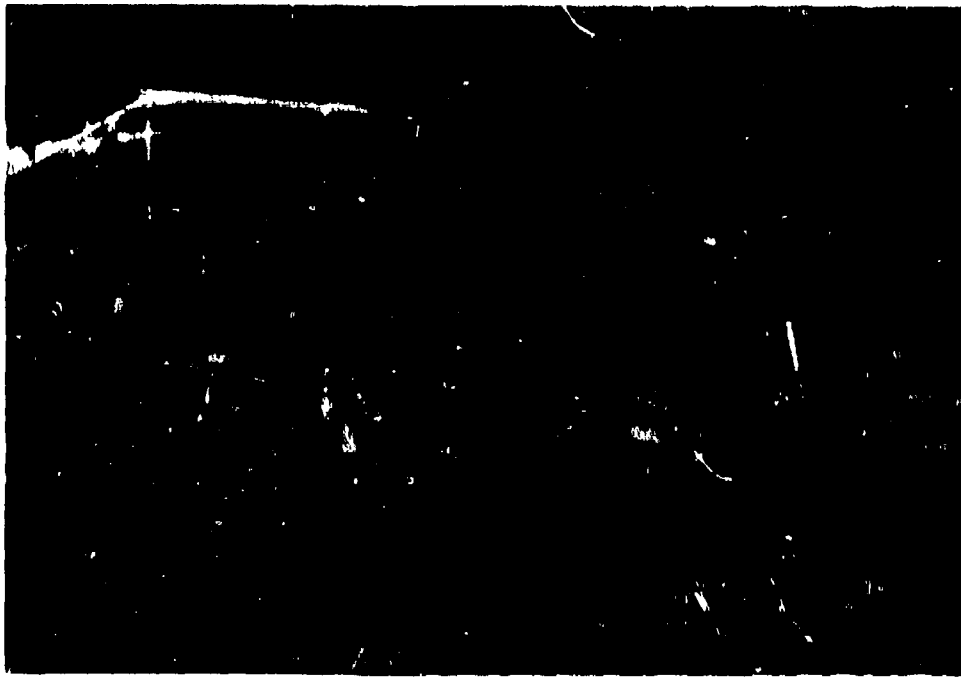
Figure 2.2 Block Diagram - Pulse Receiver

measurements, the IF signal was displayed simultaneously on the spectrum analyzer. Polaroid photographs of the displayed waveshapes provided most of the data. The x-y plotter in the oscilloscope afforded an alternate method of recording the detected pulse.

The receiver system was calibrated in amplitude by using the HP 608 signal generator tuned to the carrier frequency and pulse modulated from a 1 kHz square wave source available on the front panel of the oscilloscope. This signal, preset to a known output level, was inserted into the ACL receiver (in place of the antenna) and, following detection, the square wave envelope of the pulsed carrier was displayed on the oscilloscope. Gain levels of both the receiver and the oscilloscope were adjusted to provide the desired amplitude range of the square wave in centimeters on the graticule, thereby calibrating the receiver system.

For mobile measurements, the receiving equipment was installed and operated in a Rolligon trailer. The soft "bags" or tires on this vehicle provided relatively shock-free motion in comparison to conventional vehicles. Pictures of the Rolligon tractor-trailer, and the equipment in the trailer, are shown in Figure 2.3.

The transmitting and receiving antennas were identical resonant half-wave dipoles at each operating frequency. Preliminary tests performed in and out of the foliage have shown that the effects of foliage on the impedance of a  $\lambda/2$  dipole was negligible.



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Figure 2.3 Rolligon Tractor-Trailer  
and Equipment in Trailer

### 3. EXPERIMENTAL ENVIRONMENT

The experimental data in this report were obtained from measurements conducted in the Area II test site. The geographical relation of this area to other test sites in Thailand previously used is shown in Figure 3.1. The detailed environmental characteristics of this test site, such as forest biomass, rainfall, and other climatological data, have been described in previous reports (see SA No. 9 and No. 10).

An aerial view of the base camp in the test area is shown in Figure 3.2. The landing strip is sufficiently long for the landing and take-off of light STOL aircraft, such as the Heliocourier, used for the transportation of personnel and light supplies.

In the conduct of the measurements discussed in this report, the main access trail was carefully surveyed in distance, bearing the elevation relative to previously established survey points at the jungle site. Figure 3.3 is a map of the access trail, with elevation profile, showing the 200-foot marker sign locations, transmitter antenna location and jungle site. Marker signs were placed at 200-foot intervals along the trail and numbered consecutively, beginning with 00 at the transmitting antenna location. The first marker sign 01 is 200 feet from the transmitter, the second sign 02 is 400 feet, etc. The last sign is 48, located 9600 feet along the main access trail from the transmitting antenna. The trail from 00 to 44 is within the jungle, and from 44 to 48 is in a clearing. Points midway between the 200-foot marker signs are referred to by the appropriate decimal (e.g., 9.5 designates a point midway between marker signs 9 and 10 and is at a distance of 1900 feet along the trail). The true line-of-sight range,

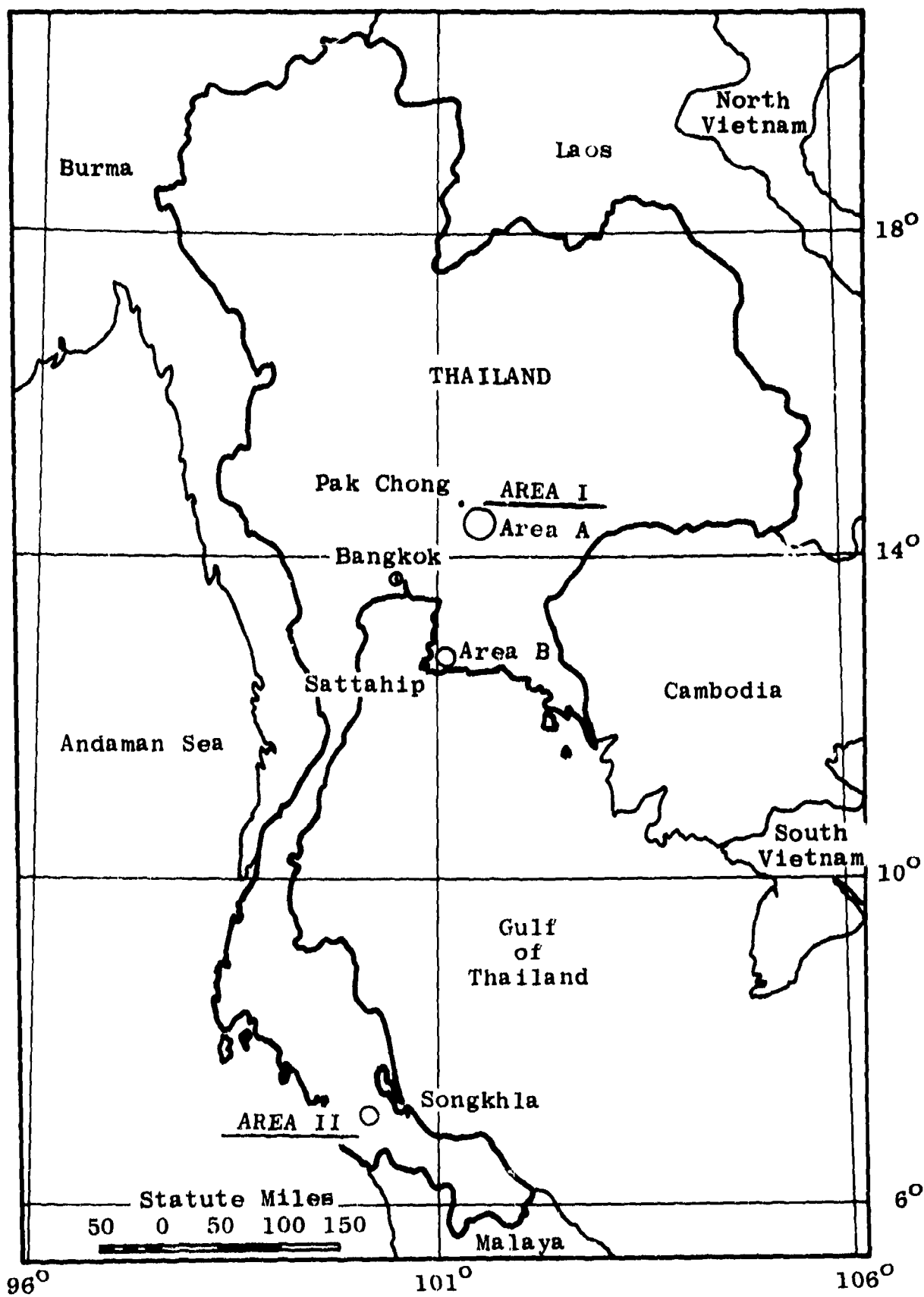
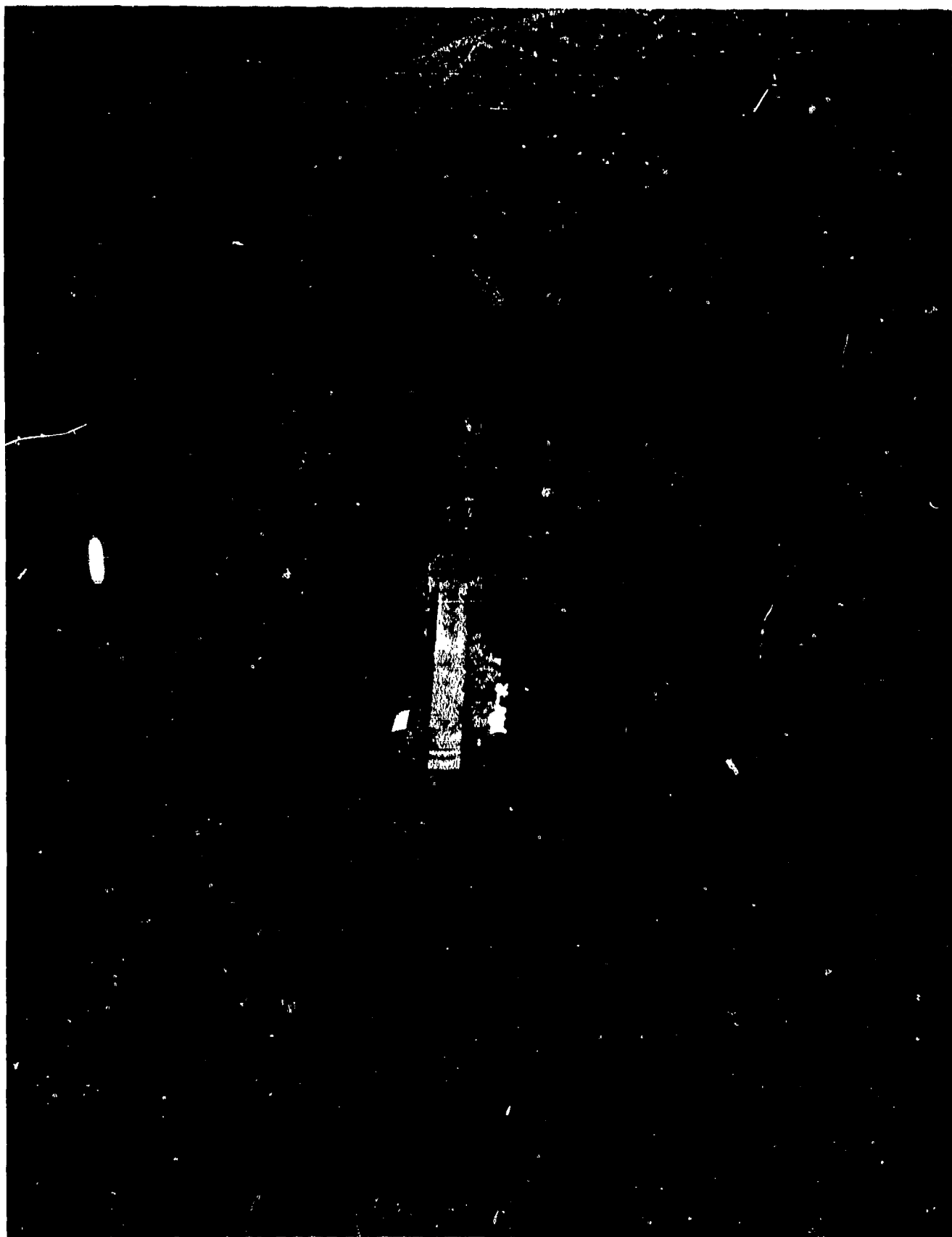


Figure 3.1 Locations of Thailand Test Areas



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Figure 3.2. J & B Base Camp and Air Strip.

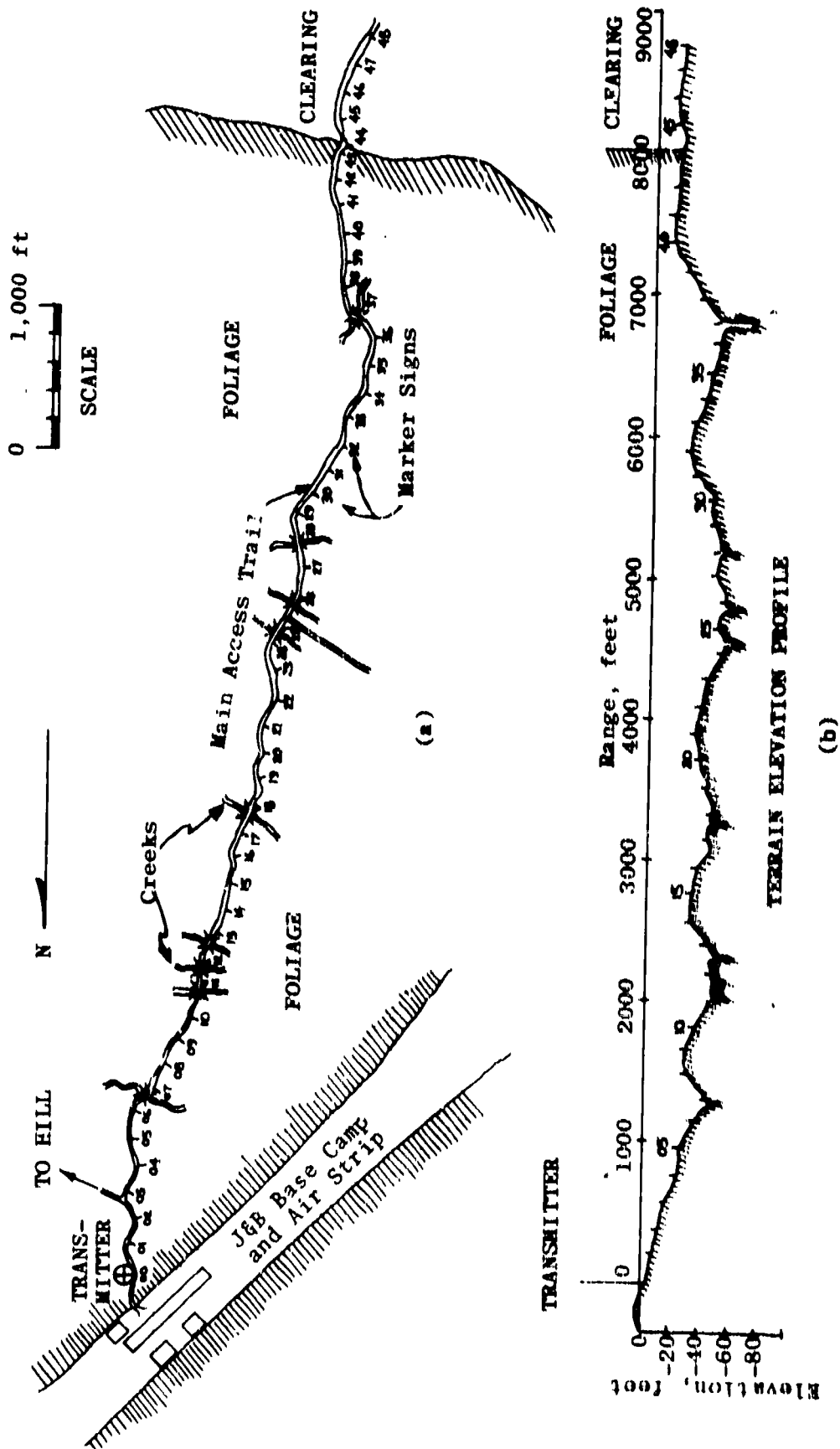


Figure 3.3 Area II Test Site Main Access Trail, (a) Plan View, (b) Elevation Profile

elevation (referenced to the transmitter) and bearing (reference North  $000^0$ ) of each trail sign are given in Table 3.1.

Localized measurements were also conducted with the receiver both on and at the base of a hill. The range, bearing and elevations of these field points were surveyed, and the results are shown in Figure 3.4.

An outline of the approximate foliage canopy along the main access trail, determined by the taller trees along the trail, is shown in Figure 3.5.

Table 3.1

Main Access Trail Markers

Ranges and elevations referenced to transmitter (Tx)

Stake No.	Range feet	Elev. feet	Bearing to Tx degrees	Stake No.	Range feet	Elev. feet	Bearing to Tx degrees
00	55	- 2		25	4,740	-47.5	012
1	195	- 7.5	000	26	4,940	-51	013
2	378	-11	005	27	5,140	-44	013
3	565	-17	000	28	5,300	-47	012
4	765	-25	005	29	5,480	-45	012
5	955	-27.5	000	30	5,660	-44	012
6	1,157	-37	000	31	5,850	-32	013
7	1,302	-44.5	008	32	6,040	-26	013
8	1,490	-31.5	010	33	6,240	-29.5	013
9	1,675	-30	011	34	6,430	-38.5	013
10	1,860	-36.5	014	35	6,630	-41.5	013
11	2,050	-47	014	36	6,830	-46	013
12	2,250	-47	013	37	6,940	-46.5	012
13	2,450	-44.5	013	38	7,110	-36	011
14	2,640	-32.5	014	39	7,300	-22.5	011
15	2,840	-32.5	014	40	7,490	-11.5	010
16	3,015	-37	014	41	7,680	-12.5	009
17	3,210	-43.5	014	42	7,880	-14	009
18	3,410	-45	014	43	8,070	-16	009
19	3,600	-41.5	014	44	8,130	-17.5	009
20	3,790	-37.5	014	45	8,320	-16.5	008
21	3,980	-33	014	46	8,520	-13.5	008
22	4,170	-37.5	014	47	8,710	-16	008
23	4,370	-40.5	013	48	8,875	-18.5	009
24	4,550	-51.5	012				

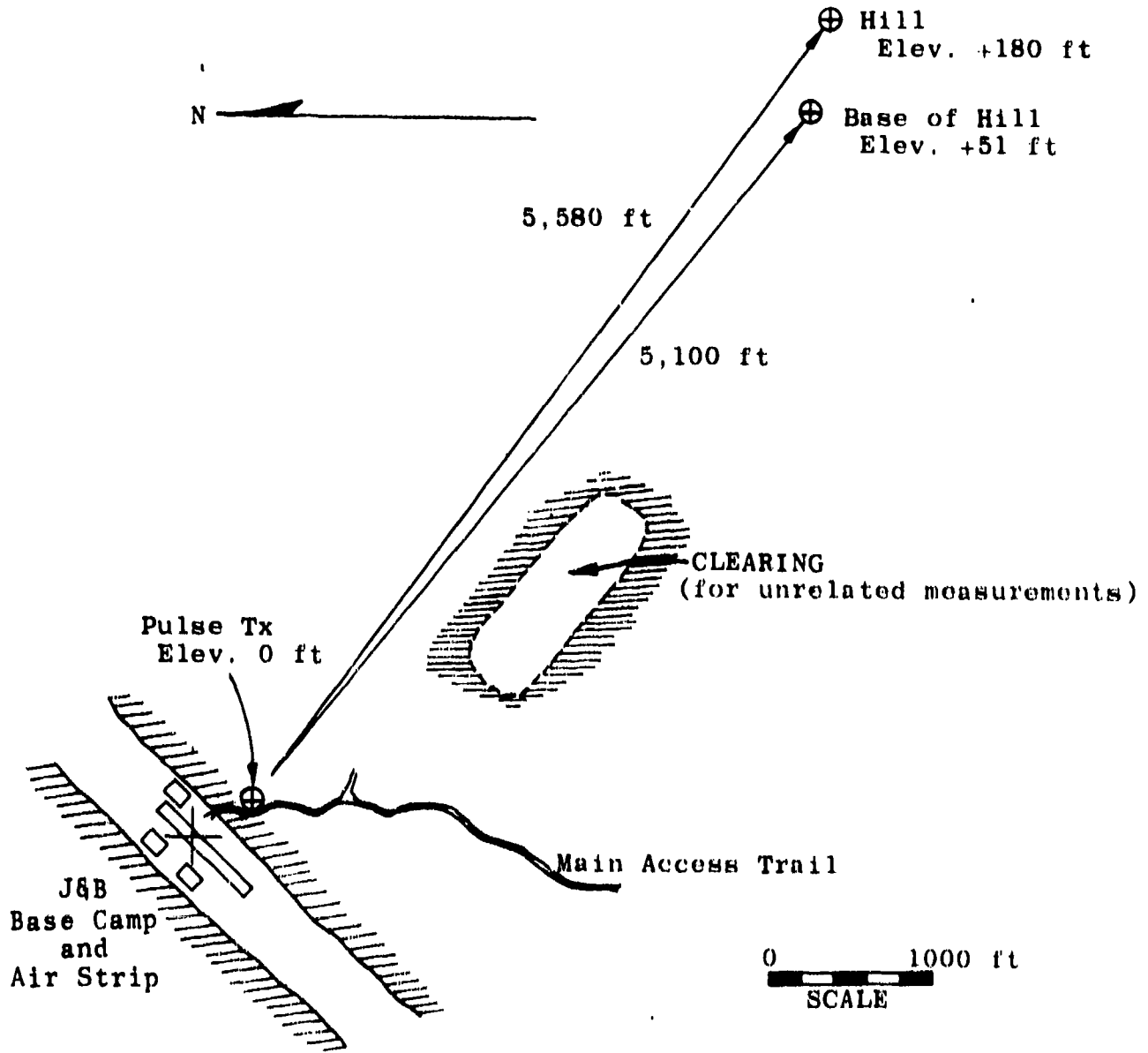


Figure 3.4 Measurement Areas at a Hill, Area II Test Site

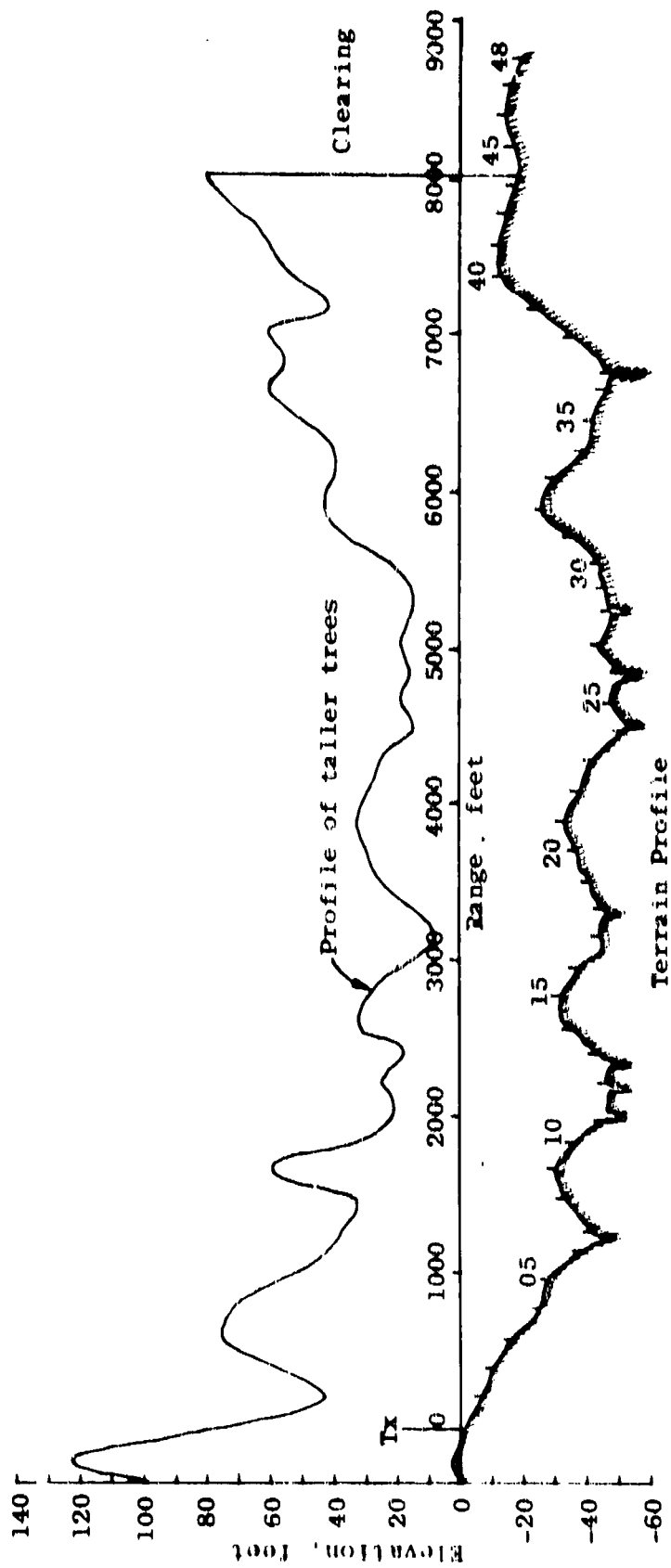


Figure 3.5 Terrain and Tree Profiles Along Main Access Trail

#### 4. PRESENTATION OF DATA AND ANALYSIS

The VHF pulse propagation data are in the form of recordings of pulse waveforms and pulse spectrum displays, or of specific characteristics of these. Square pulses of duration 1 to 6  $\mu$  sec, transmitted at a PRF of 10 kHz, were used, with carrier frequencies of 50, 100 and 150 MHz, horizontal and vertical polarizations and antenna heights from 6 to 120 feet. Pulse measurements were made over the main access trail with a mobile receiver, over localized areas with a fixed receiver along this trail, in a clearing, and at a hill. The transmitter was stationary.

##### 4.1 Mobile Pulse Measurements

The receiving equipment was mounted on a Rolligon trailer for the mobile pulse measurements. The receiving antenna was fixed at a height of 10-13 feet. During measurements with horizontal polarization, the transmitting antenna was oriented for maximum gain along the average radial direction of the trail, and the receiving antenna was oriented for maximum gain along the direction of vehicle travel. Because of the wide beamwidth of the half-wave dipoles (78%) and few pronounced curves in the trail (Figure 3.3), little pointing error is expected in fixing the horizontal antennas in this fashion. The transmitting antenna was fixed in the horizontal position and adjustable in height throughout the measurements.

Some limited tests with a mobile transmitter and fixed receiver were conducted at 100 MHz but the results did not differ

significantly from the mobile receiver-fixed transmitter measurements, and are not discussed further.\*

Three kinds of mobile measurements were made: 1) preliminary measurements, 2) pulse distortion measurements, and 3) pulse length measurements. All were for the purpose of obtaining general pulse behavior over a representative sample of the environment for different operating parameters of frequency, polarizations and antenna heights. Each utilizes the pulse amplitude only (i.e., no spectra). They differ, however, in the scope and type of data obtained, and are discussed separately in the following sections.

#### 4.1.1 Preliminary Measurements

Preliminary measurements were made to determine the behavior of the peak pulse amplitude with range for different transmission parameters. The maximum and minimum peak pulse amplitudes observed over each 200-foot increment along the main access trail were recorded. These measurements were performed with 1  $\mu$  sec duration pulses at frequencies of 50, 100 and 150 MHz with the transmitting and receiving antennas horizontally polarized, and at 100 MHz for both antennas vertically polarized. In each case the transmit antennas were at a height of 40 feet and, at 150 MHz, an additional run was performed with transmit antenna height of 13 feet.

---

\* It was found, however, that for the particular location used in these tests, the transmitting antenna could be moved over an area of  $\sim$  50 foot radius about its normally fixed position (Figure 3.4) without introducing significant changes in the received (fixed receiver) pulses. Hence, this region apparently introduced little or no distortion to the transmitted pulses.

The peak pulse amplitude measurements were converted to units of basic path loss, for comparison with previous CW path loss measurements at VHF in the environment [Jansky & Bailey, 1967], and plotted in Figure 4.1 as a function of distance. According to the lateral wave theory of VHF propagation in a densely forested environment, the mean path loss  $L_p$  is expected to increase with range  $d$  according to  $L_p \sim 40 \log d$  [Tamir, 1967; Sachs and Wyatt, 1968]. A curve with this behavior was also plotted on Figure 4.1 for comparison. It is noted that this law may not hold within the first 1000 feet or so of range due to a direct signal through the foliage, so caution should be employed in interpreting the results at the shorter ranges. The path loss obtained from the peak amplitudes of the pulses at each frequency can be seen to follow the lateral wave  $40 \log d$  curve quite well. It is also seen that the larger path loss is obtained at the higher frequencies, lower transmit antenna height, and with vertical polarization. These results are not unexpected since the pulses are bursts of CW energy and previous path loss measurements at CW have been shown to have similar behavior in this environment [Jansky & Bailey, 1967].

The difference between the maximum and minimum peak pulse amplitude measurements is plotted in Figure 4.2 as a function of distance. The minimum peak amplitude was often in noise, thus limiting the amount of useful data, but the differences in peak amplitudes appear to be independent of the range involved here. This is, again, not unexpected because similar small scale variations in path loss at CW have been found to be independent of range to much greater ranges than used here [Jansky & Bailey, 1965].

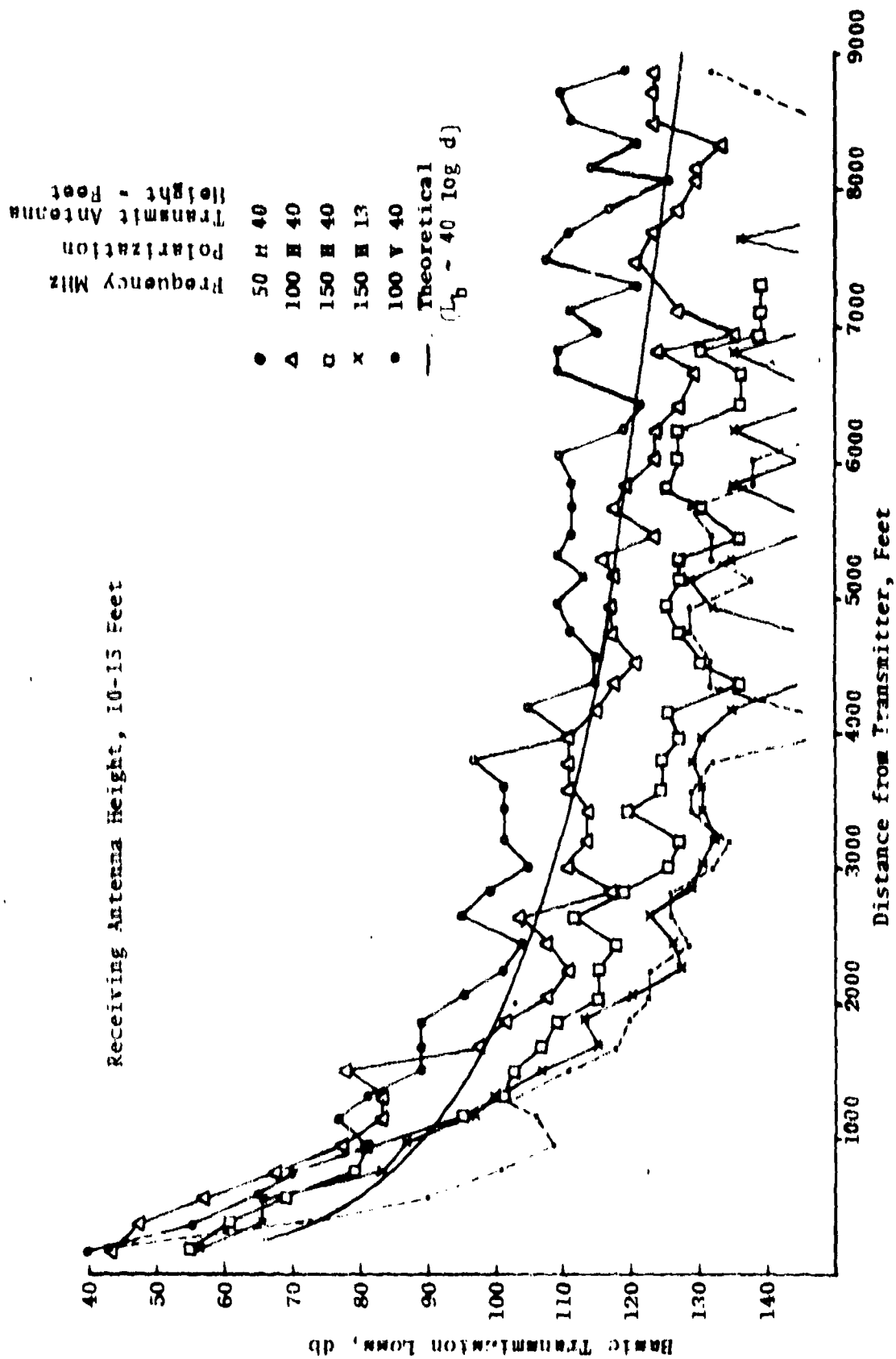


Figure 4.1 Basic Transmission Loss - Distance

Horizontal P-larity

Transmitting Antenna Height, 40 Feet

Receiving Antenna Height, 10-13 Feet

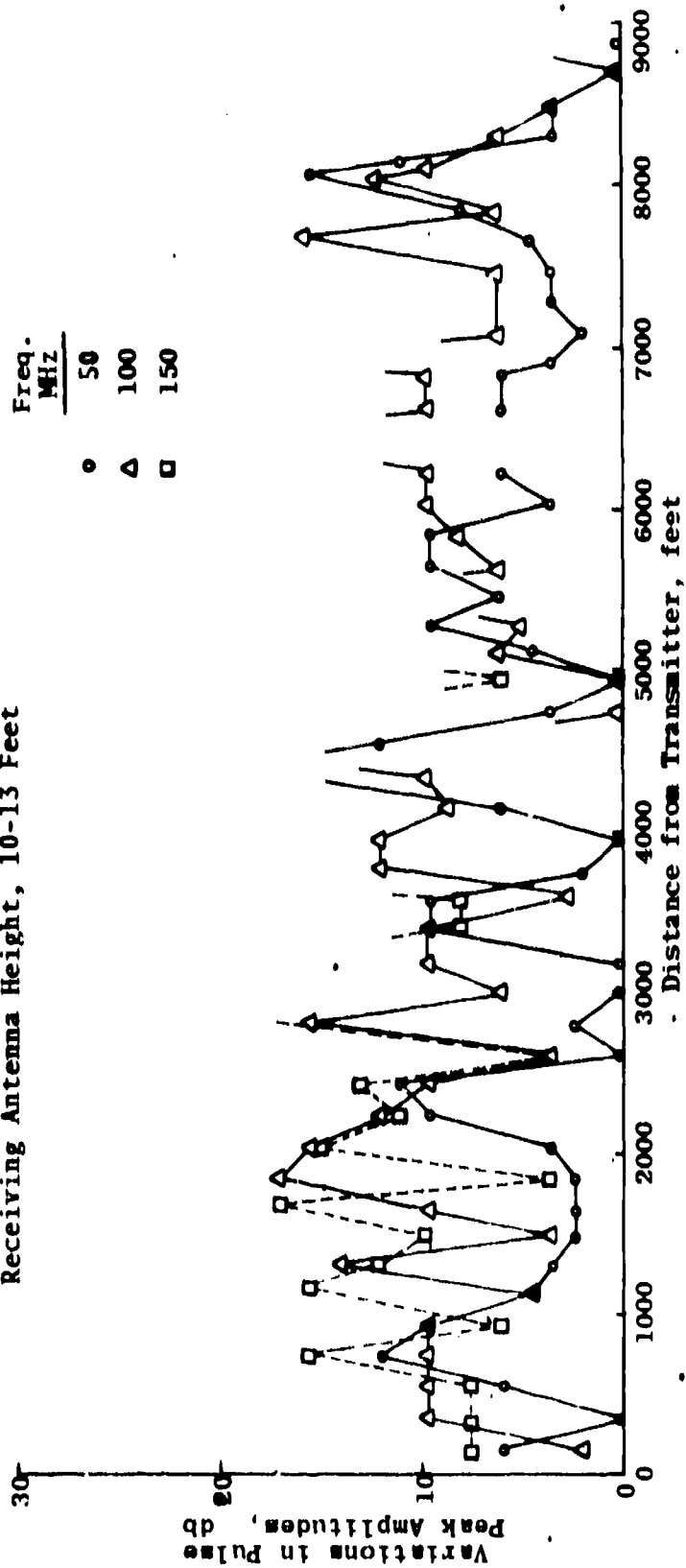


Figure 4.2 Pulse Peak Variation - Distance

#### 4.1.2 Distortion Measurements

It was observed during the preliminary measurements that the received pulses experienced various degrees of lengthening and distortion as the receiver moved along the trail. The presence of pulse distortion clearly indicates interference between pulses arriving via different paths (i.e. multipaths). Further, characteristics of the distortions may, in some cases, be related to characteristics of the multipaths, as discussed shortly. Hence, measurements were made of the pulse distortions encountered along the trail in an effort to provide insight into the extent of interference or multipaths to be expected in the environment as a whole, and to isolate areas of major distortion for further investigations.

The term distortion is quite general, however, and in order to sensibly interpret the distortions and associate them with multipath characteristics, they must be further defined. First, however, some general remarks concerning the duration of the transmitted, or sounding, pulse and the PRF are made.

A 1  $\mu$  sec duration pulse at a PRF of 10 kHz was employed and no evidence was found to indicate that there was interference between consecutive pulses at this PRF. In fact, only rarely during the preliminary measurements, and later as well, were multipaths with delay greater than  $\approx 1 \mu$  sec observed. These were evidenced by a second pulse return separated  $\approx 1$  to 2  $\mu$  sec from the main pulse on the scope display, and greatly reduced in amplitude. Thus, with rare (but possibly important) exceptions, the multipaths encountered were too short to be isolated with a 1  $\mu$  sec duration sounding pulse and the multipaths had the effect of distorting and lengthening the original pulse. Thus, distortion in general is meant here to refer only to a change in the

shape of the received pulse relative to the transmitted pulse. Hence, changes in the average signal level (such as occurs for a change in transmitted power, gain setting, etc.) and in the pulse length are ignored here in relation to distortion (although pulse lengthening and distortion are both due to multipaths). Pulse lengthening is discussed in the next section,

For the purpose of this report, the distortions are separated into two broad classes according to gross multipath characteristics as follows:

(1) Moderate Distortion - The received pulse shape differs considerably from that of the transmitted pulse, but is still recognizable as a single dominant pulse. Figure 4.3 is an illustration of moderate distortion. Moderate distortion implies the presence of two or more interfering multipaths, possibly having comparable amplitudes, with significant relative delay compared to the transmitted pulse duration and more or less random carrier phases.

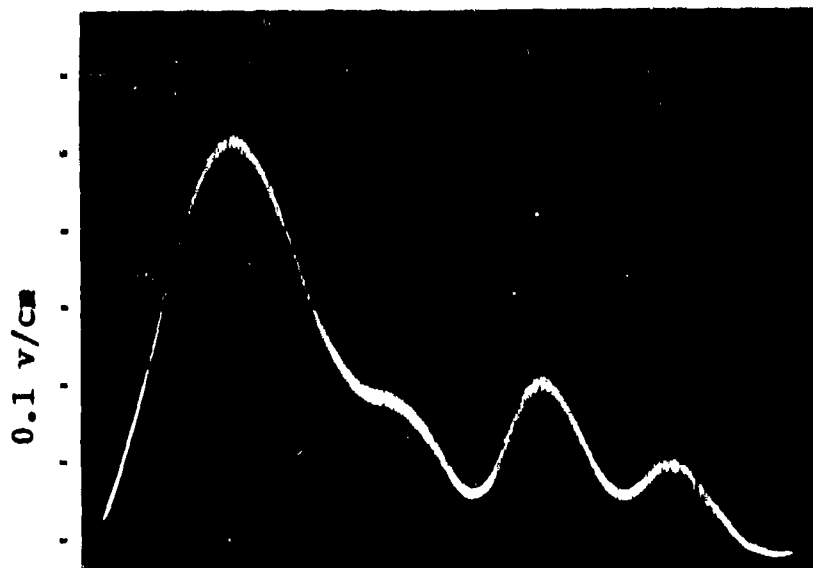
(2) Severe Distortion - The received signal appears as two distinct pulses with the amplitude minima between the two apparent pulses being  $\approx 6$  db or more below the peak amplitude of the smaller apparent pulse. Figure 4.4 is an illustration of severe distortion. Severe distortion implies that two multipaths of comparable amplitude and significant relative delay compared to the transmitted pulse duration (or groups of multipaths combining to appear as two such multipaths) are interfering destructively.

Some simple theoretical examples of interference between two pulses are illustrated in Appendix A.



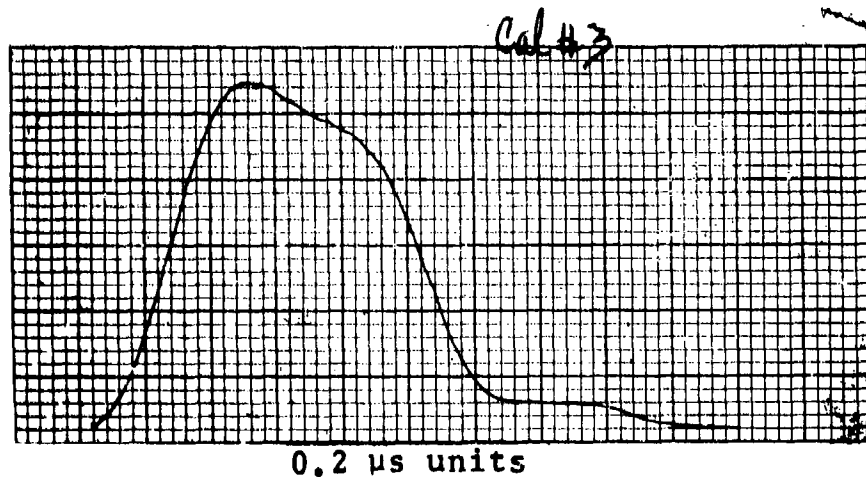
0.2  $\mu\text{s}/\text{cm}$

**Figure 4.3a** Reference Waveform at 150 MHz, Vertical Polarization, Transmitting and Receiving Antenna Heights of 13 feet, and Range of 50 feet.

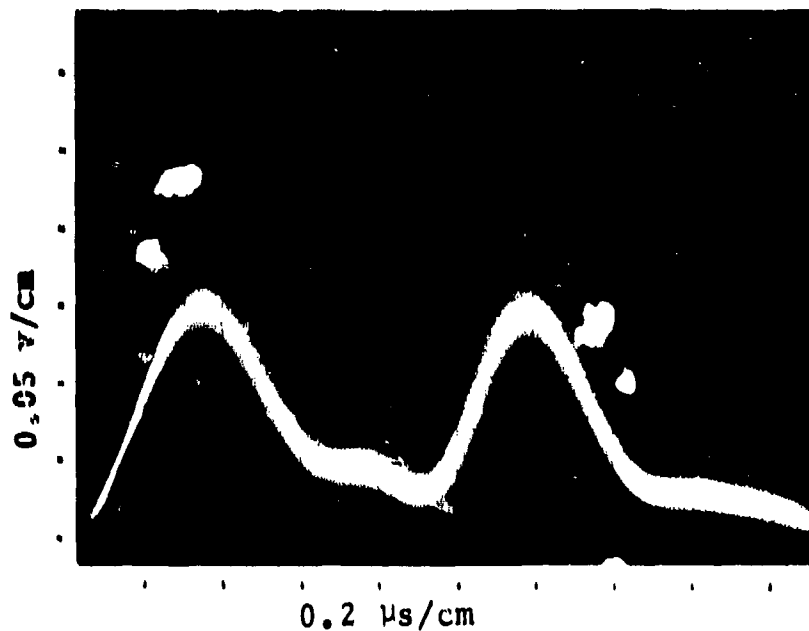


0.2  $\mu\text{s}/\text{cm}$

**Figure 4.3b** Distorted Waveform (designated moderate distortion) at 150 MHz, Vertical Polarization, Transmitting and Receiving Antenna Heights of 120 and 6 feet, respectively, and Range of 1900 feet.



**Figure 4.4a** Reference Waveform at 150 MHz, Horizontal Polarization, Transmitting and Receiving Antenna Heights of 13 feet, and Range of 50 feet.



**Figure 4.4b** Distorted Waveform (designated severe distortion) at Range of 1900 feet. Other conditions of transmission as in a, above.

Note that the leading edges of the distorted pulses of Figures 4.3 and 4.4 are not significantly different from those of the reference pulses. This was the case in all observations. Further, the earlier portions of the distorted pulses were generally observed to be larger in amplitude and undistorted, with the distortions appearing later with, generally, an accompanying average decrease in pulse amplitude. It follows that the earliest, or "direct," pulse is generally dominant and the weaker multipaths are delayed relative to the direct signal. Severe distortions, which indicate destructive interference between two (apparent) pulses of comparable magnitude is a possible exception, but even in this case the earliest pulse appears to be larger.

The received pulses were observed on the scope display as the mobile receiver moved slowly along the main access trail, from transmitter to a range of  $\approx 5000$  feet. The occurrence and approximate location of the most severely distorted pulses occurring within short segments of the trail were recorded on a Varian strip chart recorder. This was done by momentarily deflecting the marker pen to one of two predetermined levels to record the degree of distortion, and a third level was used to mark the recording each time the receiver passed a 200-foot trail marker.\*

Recordings were made for transmitting antenna heights of 13, 40, 80 and 120 feet at frequencies of 50, 100 and 150 MHz with horizontal polarization; and at transmitting antenna heights of 80 and 120 feet (lower heights resulted in the signal being too weak) at frequencies of 50 and 100 MHz for vertical polarization.

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\* A simple voltage divider circuit, composed of a battery, resistor bank and three on-off switches, was designed to provide the three levels of pen drive.

In general, the received pulse waveforms were observed to continually change in amplitude and shape (pulse ripple of 10 db and more was not uncommon) and somewhat in length, in a more or less random fashion, with receiver motion. In some cases, little distortion was observed over considerable distances, even though minor amplitude changes were occurring.

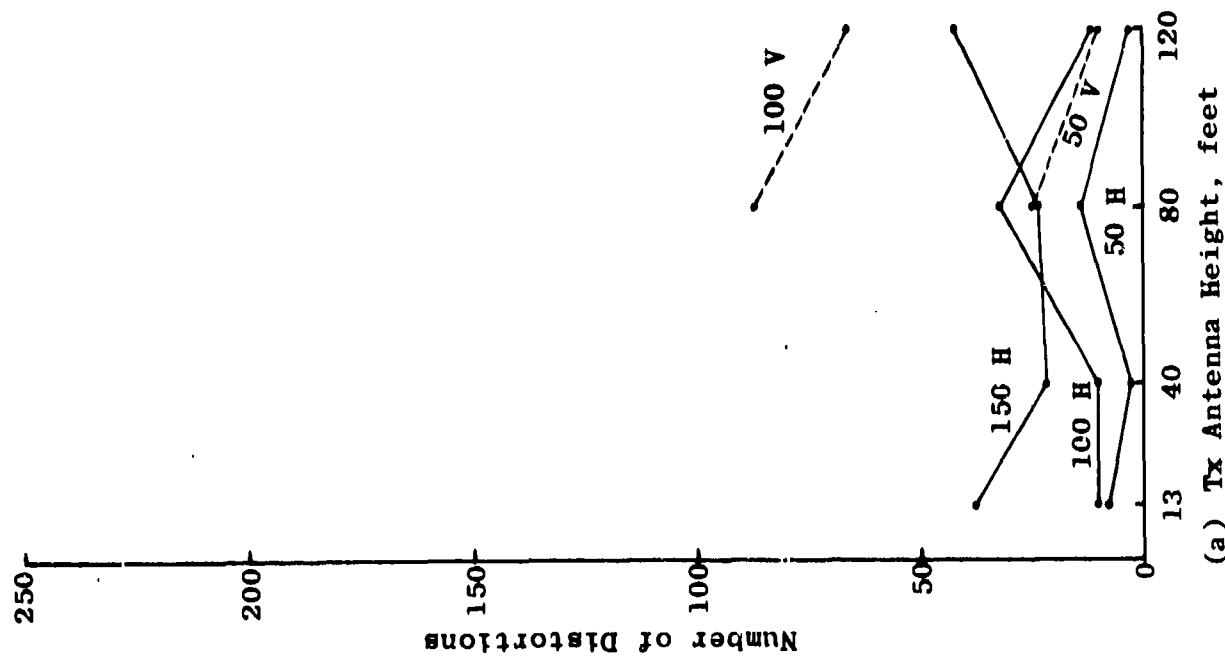
When severe distortions occurred, they persisted for only short distances (often inches), but generally repeated with distance in a quasi-cyclic fashion with spacing  $S$  being about  $\frac{\lambda}{2} \lesssim S \lesssim \lambda$ . Further, when moving through a region where severe distortions were observed, the pulse distortions generally changed with motion from severe to moderate to little or no distortion (about midway between CW minima, which are CW maxima) to moderate to severe, etc., in the quasi-cyclic manner mentioned. Moderate and less degrees of distortion, however, often occurred in the absence of severe distortion. With vertical polarization, the distortions were fairly uniformly distributed along the trail. With horizontal polarization, however, the distortions tended to cluster in groups along the trail where the over-all pulse amplitude, or mean signal strength, was at a relative low.

Table 4.1 shows the number of the worst degrees of distortions observed with each operating configuration. Figure 4.5 shows the numbers of severe and moderate distortions, respectively, as functions of transmitting antenna height, frequency and polarization. These show that in each configuration more moderate than severe distortions were encountered. This is further accentuated by recalling that observations of severe distortions imply encounters with moderate distortions as well which were not recorded. Figures 4.4a, b also show that, in general, there are fewer distortions at the lower

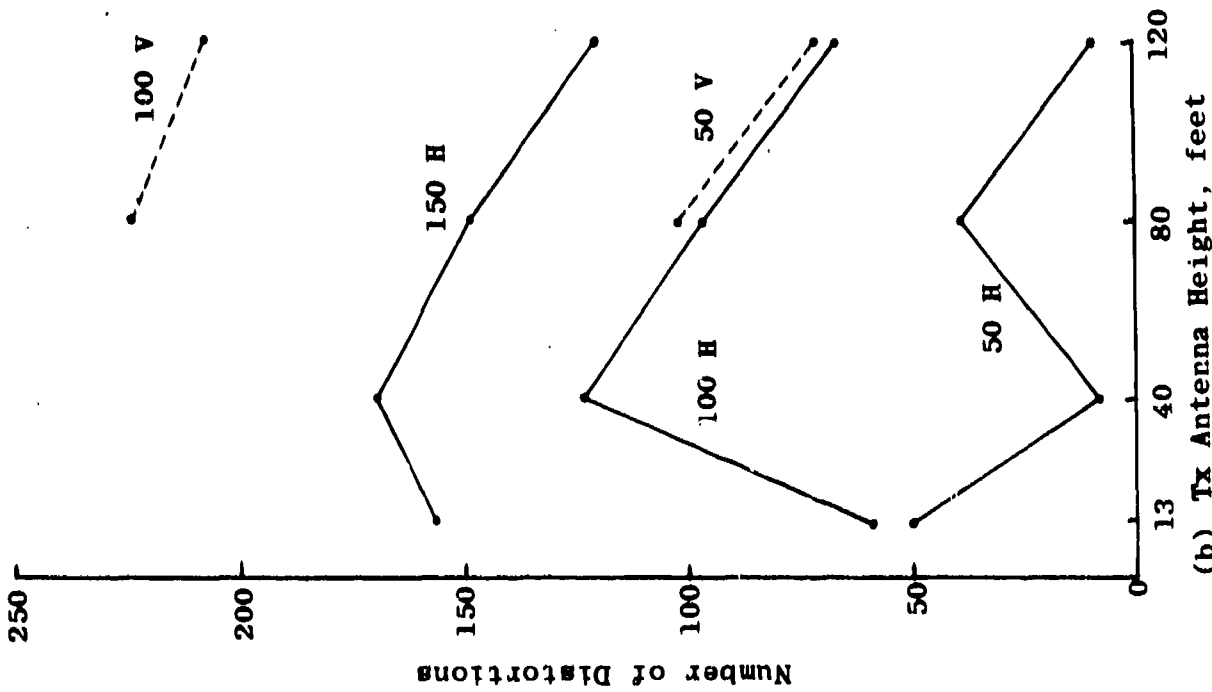
Table 4.1

Number of occurrences of distorted pulses  
observed along main access trail between  
1000 and 5000 feet from transmitter with  
receive antenna height of 13 feet.

Freq. MHz	Polarization	Transmit Antenna Height feet	Number of Distortions	
			Moderate	Severe
50	Hor	13	50	8
50	Hor	40	8	3
50	Hor	80	39	14
50	Hor	120	9	3
50	Vert	80	102	25
50	Vert	120	71	10
100	Hor	13	59	10
100	Hor	40	123	10
100	Hor	80	96	32
100	Hor	120	66	11
100	Vert	80	223	87
100	Vert	120	207	66
150	Hor	13	156	38
150	Hor	40	169	22
150	Hor	80	148	24
150	Hor	120	120	42



(a) Tx Antenna Height, feet



(b) Tx Antenna Height, feet

Figure 4.5 Number of (a) Severe and (b) Moderate Distortions as a Function of Frequency, Transmitting (Tx) Antenna Height, and Polarization. Frequency in MHz and Polarization are Identified by Numbers and Letters by Curves

frequencies for both polarizations, and that there are fewer distortions for horizontal than for vertical polarization. The number of distortions encountered also changes with transmitting antenna heights, but no trend is apparent.

The measurement of the positions of occurrences of severe distortions were too coarse to permit a reliable measurement of their spatial separation  $S$ , other than that it was generally less than  $\lambda$ . That the spatial separation is proportional to  $\lambda$  can be demonstrated, however, by normalizing the number of occurrences of severe distortions to  $\lambda$ . Figure 4.6 is a plot of the number of occurrences of severe distortion, normalized to the wavelength at 50 MHz by dividing the number encountered at 100 and 150 MHz by 2 and 3, respectively, and demonstrates that the spatial separation of severe distortions is proportional to  $\lambda$ . The agreement is not as good for vertical polarization as for horizontal, but the data are relatively sparse for the vertical, and perhaps the results should not be relied upon too heavily. It is interesting to note that deep signal minima at CW have previously been observed to recur, within a similar environment at VHF, in a quasi-cyclic manner, with spacing  $S \approx 0.74\lambda$  [Jansky & Bailey, 1966], which suggests a correlation between CW minima and severe pulse distortion. This is, indeed, the case as discussed further in Section 4.2.1.

Figure 4.7 shows the terrain profile, location and extent of the groups of distortion along the trail for horizontal polarization at each antenna height and frequency employed. The distortion regions are seen to extend from 20 to hundreds of feet along the trail. The percentage of the trail occupied by these distortions is also given. For a carrier frequency of 50 MHz, the regions of pulse distortion generally occur just beyond the crest of each hill. Correlation

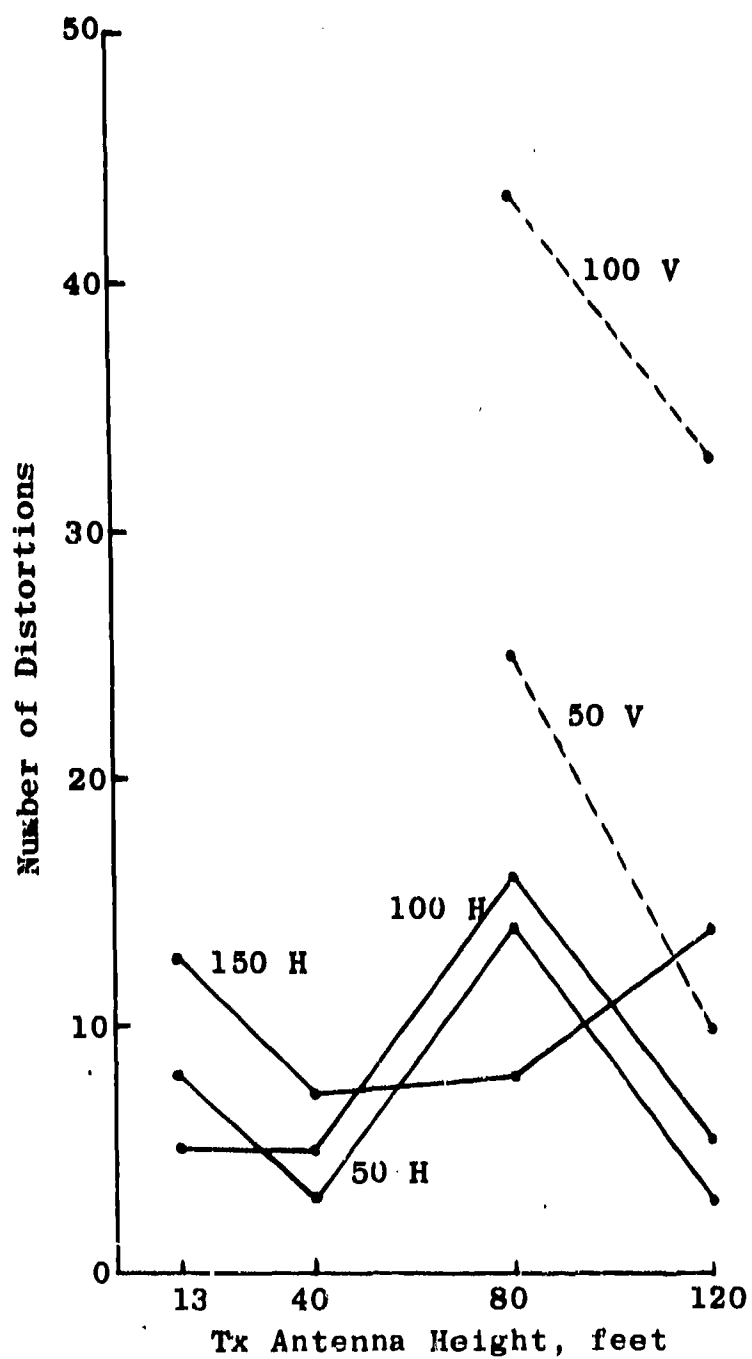


Figure 4.6 Number of Severe Distortions, Normalized to 50 MHz (Nomenclature Same as in Figure 4.5)

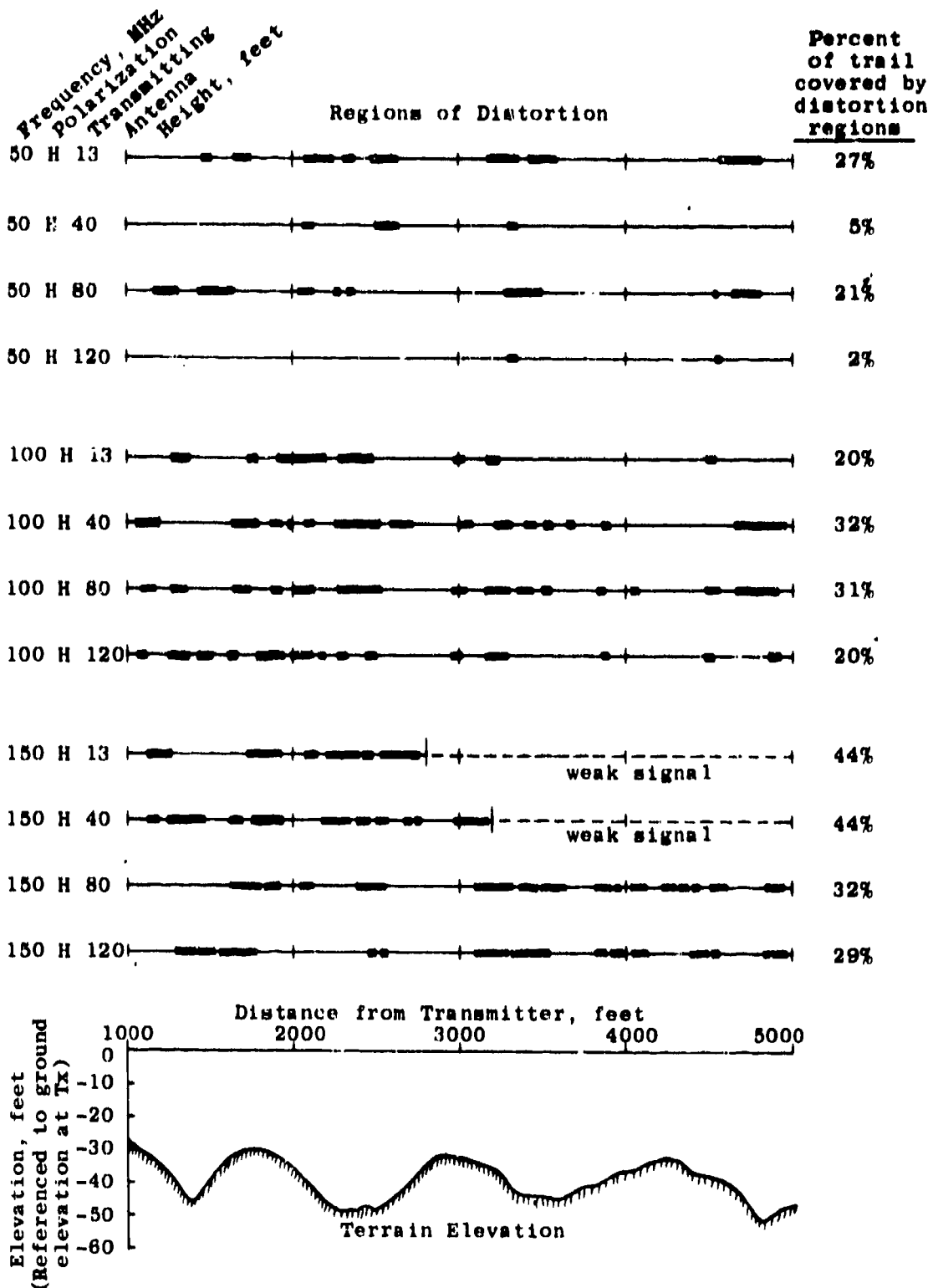


Figure 4.7 Location and Percent of Regions of Distortion Along Main Access Trail as a Function of Terrain, Frequency, and Transmitting Antenna Height for Horizontal Polarization

between distortion regions and terrain features at 100 and 150 MHz is not as pronounced. Note that changes in transmitting antenna heights result in changes in the location and extent of the distortion regions, but no regularity is evident. The thin lines in Figure 4.7 show that the larger portion of the trail introduced little or no distortion for horizontal polarization at these frequencies, although isolated occurrences of widely separated distortions, which are not shown, did occur.

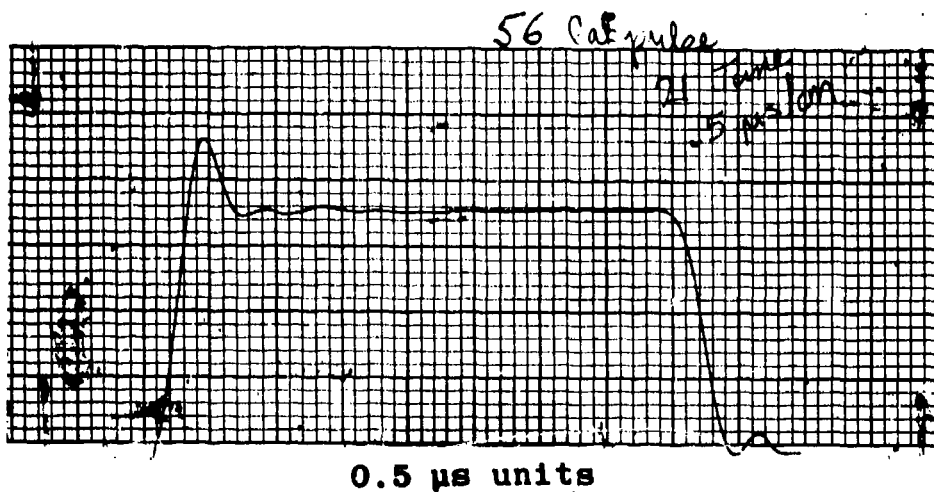
#### 4.1.3 Pulse Length Measurements

A measurement of the pulse lengthening of the received pulses relative to the transmitted pulse gives a measure of the multipath spread  $\Delta\tau$ , which, in turn, provides an estimate of the coherent bandwidth  $BW \approx \frac{1}{\Delta\tau}$  of the environment, or channel [Stein and Jones, 1967]. This section discusses measurements made to arrive at an estimate of  $\Delta\tau$ .

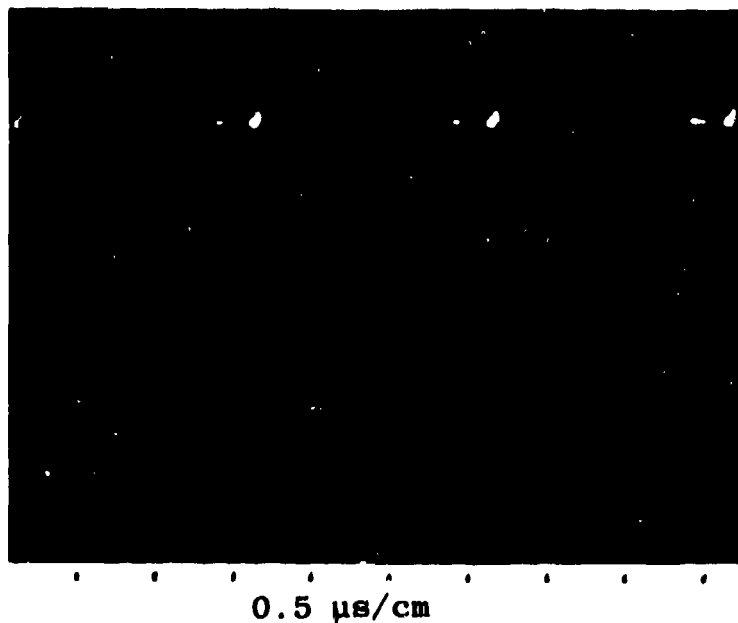
Observations of the pulse lengthening with a 1  $\mu$  sec duration pulse showed the trailing edge of the distorted pulses, generally, to blend smoothly into the noise level, making it difficult to recognize a meaningful reference for measuring pulse length. In an effort to overcome this difficulty, the transmitted pulses were lengthened to 3, 4 or 6  $\mu$  sec duration (recall that qualitative multipath delays greater than 1  $\mu$  sec were rare). In this case, where the pulse length is substantially greater than the multipath spread, the leading and trailing portions of the pulses are distorted, each portion being distorted over a distance corresponding approximately to the multipath spread, while the center portion of the pulse remains undistorted. The length of the received pulse from the leading edge to the end of the first distortion region is taken here as the multipath spread. The amplitude reference for this

measurement is the amplitude of the undistorted center portion of the received pulses. Figure 4.8 is the reference waveform and an illustrative example of a distorted pulse whose length is substantially greater than the multipath spread.

The pulse lengthening, or multipath spread, of the received pulses was observed on the scope as the Rolligon-mounted receiver was slowly moved along the main access trail from near the transmitter to about 3000 feet. At the completion of each run, comprising one combination of operating parameters, the operator recorded the largest  $\Delta\tau$  which recurred frequently enough to be definitely identified. Table 4.2 shows the operating frequency, transmitting antenna heights, transmitted pulse duration, and polarization used and the resulting approximate upper limit of  $\Delta\tau$  for each. It is noted that a few isolated delays of 2-3  $\mu$  sec were also observed, but as mentioned earlier, their occurrence was very rare and their amplitudes always greatly reduced.



**Figure 4.8a** Reference Waveform at 100 MHz, Vertical Polarization, Transmitting and Receiving Antenna Heights of 40 and 10 feet, respectively, and Range of 1600 feet.



**Figure 4.8b** Distorted Waveform of transmitted pulse much longer than multipath delay at above conditions of transmission. This photo is of a 4  $\mu$ s pulse. The delay is measured by the duration of distortion of the leading edge, in this case about 0.5  $\mu$ s.

Table 4.2 Multipath Time Spread

<u>Freq.</u>	<u>Transmit</u>		<u>Receive</u>		<u>Microsecond Time Spread</u>
	<u>Pol.</u>	<u>Ht.</u>	<u>Pol.</u>	<u>Ht.</u>	
50	H	40	H	10	1
100	H	40 & 80	H	10	1 1/2
100	V	40 & 80	V	10	1
150	H	80	H	10	1/2 to 3/4

Because of the coarseness of the determination of  $\Delta\tau$ , no attempt is made to infer differences in  $\Delta\tau$  for different frequencies, antenna heights or polarizations. It is clear, however, that  $\Delta\tau \approx 1 \mu \text{ sec}$  is a reliable order-of-magnitude estimate for the multipath spread at the frequencies employed. Consequently, the coherent bandwidth of the foliated jungle environment is  $\approx 1 \text{ MHz}$  at the VHF frequencies employed.

#### 4.2 Localized Pulse Measurements

Localized pulse measurements were made 1) in regions experiencing severe pulse distortion along the main access trail, 2) in foliage near a large clearing and in the clearing and 3) at the base of a hill and on a hill. The purpose was to associate pulse behavior with characteristics of these areas. The localized regions were  $\approx 100\text{-}200 \text{ ft.}^2$  in area. The transmitting antenna was fixed in horizontal position and its height adjustable. During measurements with horizontal polarization, the transmitting and receiving antennas were oriented with their maximum gain directions along the line-of-sight path from transmitter to receiver.

The investigations at the three general localized areas and the results are discussed separately below.

#### 4.2.1 Regions of Severe Distortion

It was pointed out in Section 4.1.2 that severe distortions tend to occur in a quasi-cyclic fashion, with spacing proportional to  $\lambda$ , along a radial direction from the transmitter. It was further noted that severe distortions tended to correlate with previously observed quasi-cyclic behavior of deep CW minima. The correlation of severe distortions with CW minima are discussed here, as well as pulse spectra and the behavior of distortions with receiving antenna height..

Localized regions of severe distortion were chosen by examination of the mobile distortion measurements. Any of several regions could have been selected since the locations of the regions generally differ for different operating parameters, as pointed out previously (Section 4.1.2). Two such regions were examined for each of the carrier frequencies of 50, 100 and 150 MHz. The ranges from the transmitting antenna to these regions were 1700 and 3300 feet for 50 MHz, 2200 and 3300 feet for 100 MHz, and 1900 and 2500 feet for 150 MHz.

The procedure at each location (and corresponding frequency) was to first transmit a CW signal with fixed transmitting antenna height, and probe about the region with the receiving antenna 6-8 feet high to locate positions of deep CW minima. The positions of CW minima, which generally differed for vertical and horizontal polarization, were then marked with stakes. Immediately following this procedure at each region the transmitter was placed in the pulse mode, and 1  $\mu$  sec duration pulses transmitted with PRP = 10 kHz. The receiving antenna was then probed about, using the same operating configuration of frequency, polarization, etc. as employed in locating the CW minima, to locate specific points of severe

distortion. Figure 4.9 contains strip recordings of the reference waveform (taken at an undistorted region) and the waveform with the receiving antenna at the location of a deep CW minima at 50 MHz. Figure 4.10 shows corresponding photographs of the spectrum. The transmitting and receiving antennas were 40 and 6 feet high, respectively, and vertically polarized. The range was 3300 feet. Note the splitting of the pulse into two parts and the reduction of the main lobe of characteristic  $\frac{\sin x}{x}$  spectrum. These are indicative of destructive interference of pulses of comparable amplitude. The reduction of the main lobe of the spectrum (i.e., at the carrier frequency) could have been anticipated, as well as the pulse splitting, at CW minima. A total of about 175 pulse waveforms and 75 spectra recordings of such measurements were made at 50, 100 and 150 MHz at the two locations of severe distortion for each frequency, with various transmitting antenna heights and both polarizations. The results are quite similar to those of Figures 4.8, 9 and 10 and are therefore not shown. These clearly showed, however, that severe distortion occurred only at (or within inches of) the position of CW minima. It was also observed that, in many cases, slight changes in receiving antenna orientation and/or position about the location of the CW minima would significantly alter the pulse amplitude and spectrum.

A qualitative correlation was observed between wind-driven motion of trees and temporal variations in pulse amplitude and spectrum displays at positions of severe distortion, with both transmitter and receiver fixed. No attempt was made to record the effects, but their presence offers virtually irrefutable evidence that the movable parts of trees or foliage are at least partially responsible for multipaths. Similar effects of wind have been noted earlier in U.S. forests [Jansky & Bailey, 1943].

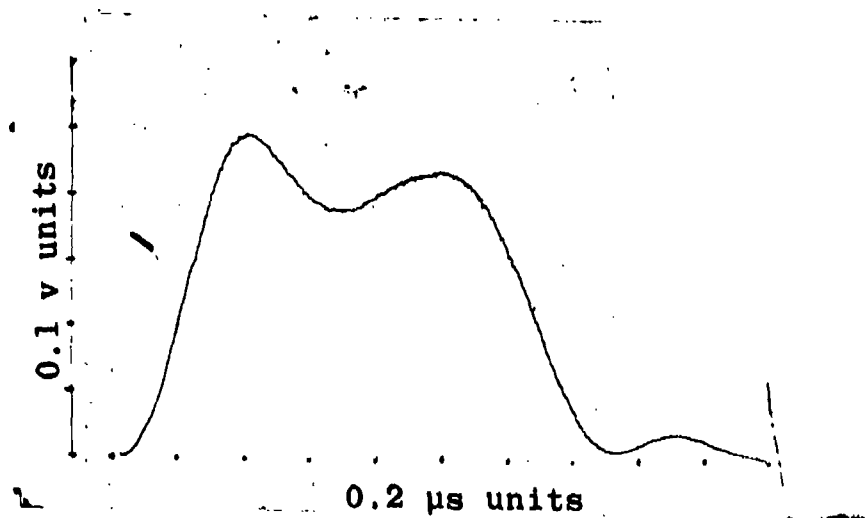


Figure 4.9a Relatively Undistorted Waveform at 50MHz, Vertical Polarization, Transmitting and Receiving Antenna Heights of 40 feet and 6 feet, respectively, and Range of 3300 feet.

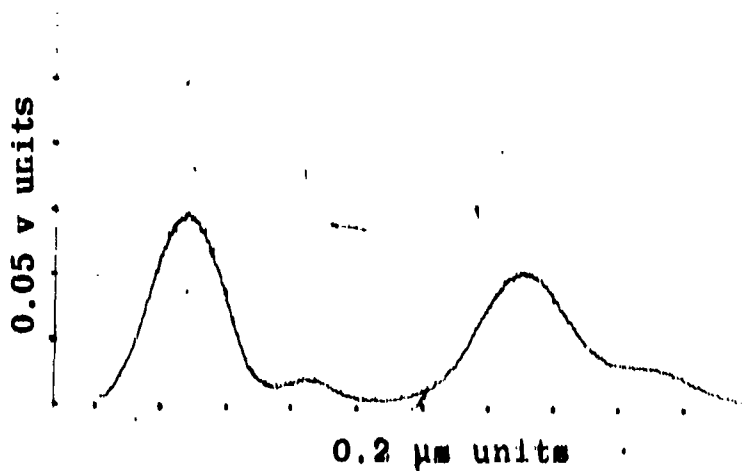
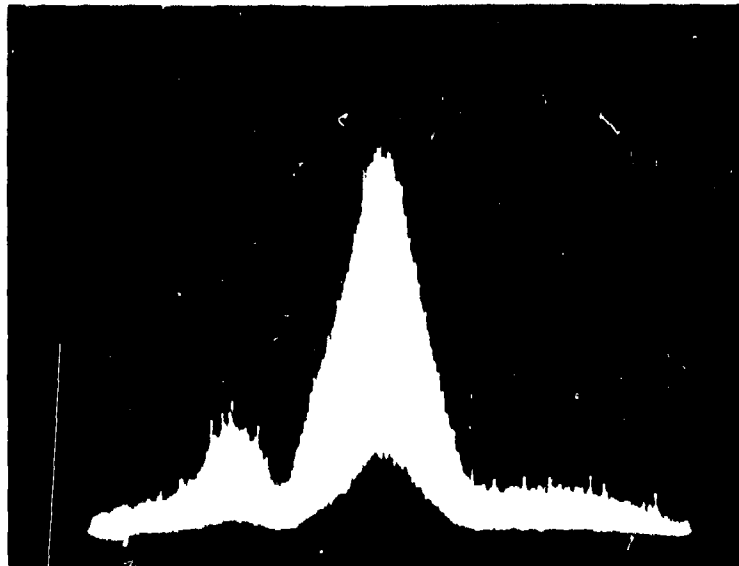
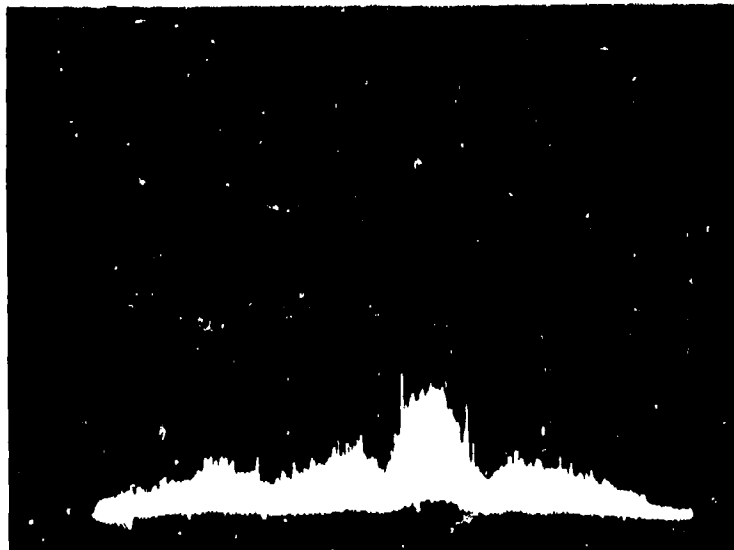


Figure 4.9b Distorted Waveform of pulse transmitted as above, but received at the location of a CW minimum at 3300 foot Range.



0.5 MHz/division

**Figure 4.10a** Spectrum centered on 50 MHz. Vertical Polarization, Transmitting and Receiving Antenna Heights of 40 and 6 feet, respectively, and Range of 3300 Feet.



0.5 MHz/division

**Figure 4.10b** Spectrum of Transmission like above, but received at location of CW minimum.

Further, not all CW minima yield severe distortion. Possible explanations for this are that the magnitude of the interfering multipaths are weaker relative to the dominant pulse or that the relative phases cause less destructive interference.

In any event, it is clear that there is a direct correlation of such minima along a radial from the transmitter, evidenced here in spacing of severe distortion, and is indicative of standing waves which have previously been observed in forested and otherwise obstructed environments [Jansky & Bailey, 1943; Egli, 1957; Jasik, 1961; and others] and from individual trees [Englund, et al., 1933; Steele, 1967; Lorchirachoonkul, 1967]. The fact that  $S \approx \lambda$  is indicative of energy arriving from somewhere behind the receiver and interfering with a forward propagating (apparently dominant lateral wave path) pulse (Appendix B). The spatial fading can be related to time fading through fade rate = velocity/(spatial fade separation in wavelengths) [Egli, 1957].

The above investigations were all done at the lower receiving antenna heights. The severity of distortions as a function of receiver height, however, was examined here at the six regions of severe distortions utilized in correlating CW minima with severe distortions. In general, the receiving antenna was probed about, as much as practicable, at various heights from 6 to 80 feet to locate the most severe degree of pulse distortion at each chosen height. The amount of probing decreased, however, with increasing height (the guy ropes were pulled to sway the antenna at the greater heights). The most severe degree of distortion observed was recorded (photographically) for each of the several combinations of frequency, antenna height and polarization. The degree of distortions is

given in Table 4.3 with each block showing the worst degree of distortion obtained at each combination of antenna height, frequency, and polarization.\*

The results show that the worst degrees of distortion are obtained at the lower receiving antenna heights with no discernible dependence on the height of the transmitting antenna. These results are biased at the receiver location, however, because the greater amount of probing to locate the distortion was done at the lower heights. Yet some probing was done with higher antennas and no severe distortions were found when both antennas were at heights of 20 feet and above, and only two encounters of moderate at 20 feet and above. Thus, while no quantitative height dependence can be established from these results, it seems clear that the distortions are more severe for the lower (6-13 foot) antenna heights. This may be caused, again, by the amplitude of the dominant pulse (presumably lateral wave path) increasing with height relatively more rapidly than did the scattered pulse amplitudes. No significant polarization or frequency dependence to the distortions are apparent from these data. The peak pulse amplitude tended to increase with increasing antenna height, as expected from the preliminary measurements (Section 4.1.1), but the data are too few to be quantitatively definitive.

#### 4.2.2 Pulse Measurements In Forest Compared to Clearing

To gain insight into the effects on pulse transmissions when operating in a clearing compared to those of operating in a forested environment, pulse measurements were made with the

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\* The distortions obtained at the base of a hill, discussed later, are also included in these data because it was a region of severe distortion.

Table 4.3

Degree of distortion obtained with different transmitting antenna heights,  $H_T$ , receiving antenna heights,  $H_R$ , frequencies, and polarization. S denotes severe, M, moderate, and N, little or no, distortion. W means signal too weak to determine distortion, and a blank, no measurement. Frequency and polarization are shown above each block.

50 MHz, Horizontal

$H_R$ feet	$H_T$ , feet				
	6,13	20	40	80	120
80	N			N	
40	M		N		
20	S	N	N		
6,13	S	N	S	M	M

50 MHz, Vertical

$H_R$ feet	$H_T$ , feet				
	6,13	20	40	80	120
80	S			N	
40	S		N		
20	M	M			
6,13	M	N	S	N	S

100 MHz, Horizontal

$H_R$ feet	$H_T$ , feet				
	6,13	20	40	80	120
80	N				
40	N		N		
20	N	N	N		
6,13	S	S	S	S	S

100 MHz, Vertical

$H_R$ feet	$H_T$ , feet				
	6,13	20	40	80	120
80	N				
40	N		M		
20	W	W			
6,13	W	W	W	S	S

150 MHz, Horizontal

$H_R$ feet	$H_T$ , feet				
	6,13	20	40	80	120
80	N			N	
40	N		N		
20	N	M	N		
6,13	S	S	S	S	S

150 MHz, Vertical

$H_R$ feet	$H_T$ , feet				
	6,13	20	40	80	120
80	N				
40	N				
20	W	W			
6,13	W	W	W	S	S

receiver located over relatively smooth terrain just inside and outside of a forest-clearing boundary. The measurement regions, identified in Figure 3.3, were along the main access trail at ranges of about 8200 feet and 8400 feet for the forested and cleared regions, respectively, with the boundary at about 8800 feet. Various combinations of antenna heights and horizontal and vertical polarization at the frequencies of 50, 100 and 150 MHz were used. Again, 1  $\mu$  sec duration pulses were transmitted and the receiving antenna was moved about, at fixed heights over a small area. The worst pulse distortions obtained over these small areas were photographically recorded. The data consisted of 70 photographs. The peak pulse amplitude and degree of distortion were determined from each.

The differences in the peak pulse amplitudes, normalized to equal transmitted powers and for corresponding frequencies, antenna heights and polarizations, between the forested and cleared regions were computed. These are shown in Table 4.4 for the combinations of antenna heights common to both regions.

The results show that the signal is generally, although not always, stronger in the clearing than the forested environment. This is consistent with early results of measurements at forest-clearing boundaries at HF and UHF and the rise of signal in the clearing was attributed to diffraction [Jansky & Bailey, 1943; Hoad, 1960].

At transmitting antenna heights of either 80 or 120 feet and receiver heights of 6 feet, moderate distortions at both polarizations and each frequency, except the 150 MHz-horizontal polarization combination, were obtained in the forested area. A single severe distortion was observed in the forested region and occurred at 100 MHz, vertical polarization,

Table 4.4

Peak pulse amplitudes in clearing, minus peak pulse amplitudes in forest, in db, for different transmitting antenna heights,  $H_T$ , receiving antenna heights,  $H_R$ , polarization, and frequency. Blanks mean no data were obtained. Frequency and polarization are shown above each block.

50 MHz, Horizontal

$H_R$ feet	$H_T$ , feet			
	20	40	80	120
6	2.9	6.1	2.7	7.7

50 MHz, Vertical

$H_R$ feet	$H_T$ , feet			
	20	40	80	120
6			6.8	

100 MHz, Horizontal

$H_R$ feet	$H_T$ , feet			
	20	40	80	120
40		0.4		
6			27.2	0.9

100 MHz, Vertical

$H_R$ feet	$H_T$ , feet			
	20	40	80	120
6			-2.5	10.1

150 MHz, Horizontal

$H_R$ feet	$H_T$ , feet			
	20	40	80	120
6			-14.5	-8.3

150 MHz, Vertical

$H_R$ feet	$H_T$ , feet			
	20	40	80	120
6			15	20

with transmitting and receiving antenna heights of 120 and 6 feet, respectively. All other combinations yielded little or no distortion in the forest, and in all cases only little or no distortion was observed in the clearing. Hence, multipath effects are less significant in the clearing than in the forest. This suggests that the scattering, or multipaths, are due to trees in the vicinity of the antennas, as discussed further in Section 5. But, from the present data it is also possible to infer that the mean signal level has increased sufficiently in the clearing, relative to the scattered components, which results in little interference, from whatever source.

The behavior of the peak pulse amplitude with height, polarization and frequency was consistent with the preliminary measurements (Section 4.1.1), although the data are too few to be quantitatively definitive.

From signal strength and pulse distortion considerations, the results indicate the desirability of operating in a clearing. It should be remembered, however, that the transmitter was located in a relatively distortion-free region. If it had not been, some degree of distortions would also have been expected in the clearing, although probably not as severe as in the forest. Also, the relative size of the clearing and the proximity of the receiving antenna to the forest clearing boundary may, conceivably, cause different results.

#### 4.2.3 Pulse Measurements Near a Hilltop and the Base of a Hill

To gain insight into the effects on pulse transmission when operating at areas of depressed and elevated terrain, pulse measurements were made with the receiver located near the top and base of a foliated hill. The regions at the base of the hill

(on the transmitter side) and near the hilltop, identified in Figure 3.4, were at ranges of 5100 feet and 5580 feet, respectively, from the transmitter. The receiver site near the hilltop was  $\approx$  130 feet higher than that at the base of the hill. The former afforded a near line-of-sight to the transmitter.

The same procedures and operating configurations as employed in the previous section were used, except tests with the transmitting antenna below 40 feet were not performed because the resulting signals at the base of the hill were too weak to permit comparison with the hill measurements. The data consisted of about 95 photographs of the pulse waveforms.

The differences in the peak pulse amplitudes, normalized as in the previous section, between the base of the hill and the hill are shown in Table 4.5. The results show that the signal is consistently stronger on the hill than at the base of the hill. Also, distortions at the base of the hill were similar to those encountered in the regions of severe distortion along the trail and have been included in the analysis of Section 4.1.2. The distortions were moderate or less on the hill with only one severe distortion located. These results are intuitively attributed to signal reception on the hill being, at least partially, via line-of-sight from the transmitter.

Table 4.5

Peak pulse amplitudes on a hill, minus peak pulse amplitudes at the base of the hill, in db, for different antenna heights, frequencies, and polarizations. Explanation of data is the same as for Table 4.4.

50 MHz, Horizontal				
H <sub>R</sub> feet	H <sub>T</sub> , feet			
	20	40	80	120
40		12.1		
20		15.1		
13		20.3		
6		18.0	17.7	15.6

50 MHz, Vertical				
H <sub>R</sub> feet	H <sub>T</sub> , feet			
	20	40	80	120
6		22.4		

100 MHz, Horizontal				
H <sub>R</sub> feet	H <sub>T</sub> , feet			
	20	40	80	120
40		7.7		
20		5.8		
13		10.4		
6		12.5	7.9	24.8

150 MHz, Horizontal				
H <sub>R</sub> feet	H <sub>T</sub> , feet			
	20	40	80	120
40		24.1		
20		29.6		
13		40.5		
6		28.8	29.8	43.2

## 5. PRELIMINARY SCATTER MODEL

The results discussed in the previous sections suggest an extension to the homogeneous slab model of propagation which holds at HF and much of VHF in the foliated environment to include scattering from trees. Such a model is presented here in general terms, shown qualitatively to explain a number of the experimental results obtained thus far.

First, a brief review of the concepts of the lateral wave mode of propagation in a forested environment, which provides the basic foundation of the scatter model, will be helpful. According to the lateral wave theory, propagation is from the transmitter, immersed in the foliage, upward through relatively highly attenuating foliage, at the small critical angle of total internal reflection, to the forest canopy-air interface. It then travels along this interface with the field strength decreasing as distance squared and with energy leaking downward, at the angle of total internal reflection, through the highly attenuating foliage to the receiver. The relatively high attenuation rate of the signal in passing through the foliage is an important consideration. There is a field near and above the forest canopy-air interface which also propagates according to the inverse distance squared law of the lateral wave [Sachs, 1966]. Note that the forest canopy-air interface is at some "effective" height above the ground which is less than the height of the taller trees for a forest with nonuniform tree heights. Now, assuming single scattering, the model of Figure 5.1 is suggested. For simplicity, only one scattering element near each terminal and above the effective canopy height is shown. Path ABC is the lateral wave path, path AD is the field above the interface, assumed scattered by a tree near the receiver with the scattered signal traveling along path E to

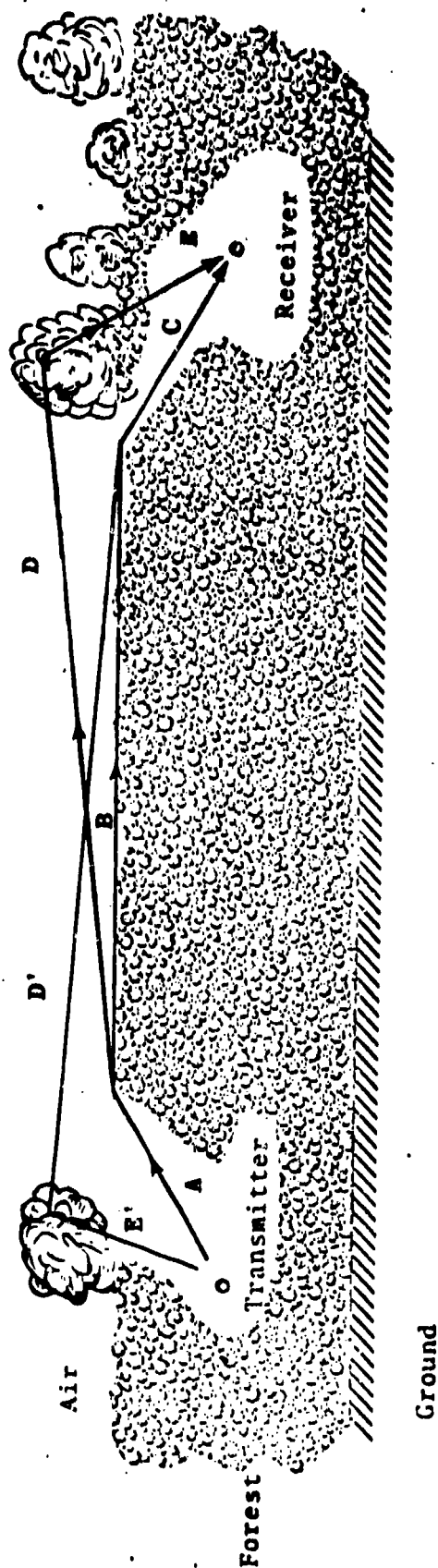


Figure 5.1 Sketch of Ray Paths in Scatter Model

the receiver. Path E is assumed to be a line-of-sight path and refraction of the ray along E is assumed negligible. E'D'C is analogous to path ADE and represents scattering from near the transmitter. The transmitter and receiver are assumed to be separated a distance large compared to path E or E'. Hence, with the assumption of single scattering, the signal scattered from near the transmitter finally arrives at the receiver along, virtually, path C of the lateral wave. The signals therefore arrive at the receiver (with only one scatterer being considered for the moment) along only two paths; one is essentially the lateral wave path and the other is by line-of-sight from the scatterer near the receiver.

The scatterers are purposefully shown to be near the antenna terminals. That this is the case is evident by the fact that the short spatial or fine-grain signal variations are independent of range [Jansky & Bailey, 1965]. Further, scattering originating a far distance from the antenna terminals is generally required to pass through more of the highly attenuating foliage (probably equivalent to the length of C) than is scattering originating from near the terminals, and therefore is proportionately less effective. Some approximate limits may be ascribed to the regions of effective scattering about the antennas from the pulse lengthening measurements of Section 4.1.3. A delay of  $\Delta\tau \approx 1 \mu \text{ sec}$  was found in Section 4.1.3 and if a line-of-sight path from a scatterer directly behind the receiver is assumed (the shortest scatter path for a given delay time), the scatterer is located  $\approx c \frac{\Delta\tau}{2} \approx 500 \text{ feet}$  behind the receiver, where  $c$  is the speed of light. If the scatterers have a directional scattering pattern which results in substantially more energy being scattered in the horizontal plane at, say, right angles to the path of the incident energy, then this estimate may be low because the scatter path is then longer for a given

delay than is the backscatter path. From experimental results of the scattering pattern of trees at VHF [Lorchirachoonkul, 1967], however, there appears to be little directivity in the scatter pattern of a single tree. At any rate, it seems clear that effective scattering must originate from near the vicinity of the antennas (excluding anomalous scattering from airplanes, large terrain obstacles, etc.) rather than throughout the general environment. The qualitative model is completed by simply assuming more scatterers within this effective scattering region about the terminals. Some of the more salient factors requiring further clarification to place the model on a quantitative basis are mentioned later, but it will be helpful to first review the experimental results in light of the model.

From the model, the quasi-cyclic spatial variations, with spacing between minima  $<\lambda$ , encountered when the receiver is in motion along a radial from the transmitter, are indicative of energy scattered from behind the receiver interfering with the forward energy along the lateral wave path C (Appendix B). Further, scattering from the region about the transmitter does not contribute directly to these short spatial variations with the mobile receiver, other than to alter the initial amplitude and phase of the signal arriving via path C. This is because the change in relative path length (or phase) between the lateral wave and the signal scattered from near the transmitter is negligible compared to the relative path length (or phase) changes between the signal scattered from near and behind the receiver and the lateral wave (or lateral wave plus scattered from near the transmitter) when the mobile receiver is moved over short distances. If the transmitter were mobile and receiver stationary in the same forested environment, however, reciprocity would require the same short spatial fading of the received signal, and scattering originating near the receiver

would have the same small effect as that originating near the transmitter for a mobile receiver. Hence, short spatial fading should result with either or both antennas in motion. There may be scattering from in front of the antennas as well, resulting in quasi-cyclic fading with spacing between fades being greater than  $\lambda$ . Long cyclic spatial variations are not readily evident in the data, probably because of the terrain influence on mean signal strength.

The signal fading resulting from antenna motion (either antenna) is termed spatial fading here. It can be related to the usual time fading through the equation of speed = distance/time, as done by Egli [1957]. Frequency selectivity is also implied, if the signal bandwidth is not sufficiently less than the coherent bandwidth of the channel [Schwartz et al., 1966]. From the model, the frequency selectivity is expected to be nearly independent of range, other things being equal, because the differences in the path lengths are practically independent of range. Also, it is clear that the channel may be frequency selective with or without antenna motion. In the latter case, the frequency selectivity is fixed (providing the wind effects are negligible) and thus differs from the troposcatter, ionospheric and other dynamic frequency selective channels which have received the most attention. Also, frequency selectivity may be quite pronounced in deep fades, or signal minima, even where the bandwidth is sufficiently limited to allow normally reliable operation [Schwartz, et al., 1966]. This may pose serious problems to digital operations in forested environments because of the deep fades at standing wave minima. Mobile operations would normally encounter such deep fades, at times with regularity (Section 4.1.2), and stationary antennas could possibly be located in positions of such fades, although they occupy relatively little space (Section 4.2.1).

The fact that the leading edges of the received pulses were similar to those of the transmitted pulses indicates that the earliest pulse, arriving via the lateral wave path according to the model, is generally the stronger (Section 4.1.3). Severe distortion is a possible exception, as also pointed out in Section 4.1.3. The model, in its present crude state, does not permit determination of why, or under what circumstances, the interfering signals (lateral wave and scattered) can be expected to be of comparable, or any other predetermined, magnitude. However, any change in the lateral wave path length, such as by terrain influences as suggested by results of Section 4.1.2, or in the scattered field effectiveness, as may result for different size trees appearing at different distances in the effective scattering region of the terminals, may yield different results. Further investigation is needed in this, as the results could be quite important to optimum location of terminals as well as diversity systems.

The distortions were also found to be less severe for the higher receiving antennas independent of transmitting antenna heights (Section 4.2.1). This could have been anticipated from the model, because the lateral wave (generally the dominant) is expected to increase in magnitude at a greater rate with increasing receive antenna height than does the signal scattered along path E. This is because path C, at a small elevation angle through the highly attenuating foliage, decreases by a greater amount with increasing receiving antenna height than does the more direct scattered signal path E if the scatterer is above the receiver. Hence, the dominant signal becomes more dominant and relatively less affected by interference from scattering. This effect is further accentuated if the scattered signal path E increases with increasing receive antenna height, in which case the scattered signal is reduced, as would be the case for

scattering from heights less than receiver antenna height (say from the lower portion of the tree trunks).

On the basis of the magnitude of the incident energy striking a scatterer above or below the effective canopy height, scattering from above the canopy is favored (this is due to the higher attenuation along an incident lateral wave path for scatterers in the foliage). However, the scattering coefficient of a tree may be greater for the larger lower trunk portion than the upper which would tend to offset the greater loss of incident energy through the foliage. It is clear, of course, that some scattering must result from the upper, wind-movable portions of the trees since temporal signal variations were observed here and elsewhere in forest environments [Jansky & Bailey, 1943]. Further, the environment of this report was characterized by occasional large trees emerging to heights of 120 feet and greater, whereas the average canopy height (although as yet undetermined) was considerably less, perhaps 50 to 80 feet. In a forested environment having such emergents, it is intuitively expected that these larger trees, which generally have considerable trunk diameter at or near the effective canopy height, will dominate the scattering. If this be the case, then it follows that an examination of the upper canopy by, say, remote aerial photographic procedures, may provide sufficient data to determine the major multipath characteristics of the channel. This may be an important consideration when tactical operations, especially at short range, are anticipated in a hostile environment. Further investigations, both theoretical and experimental, are required to determine the effects of the large emergent trees.

The model may be used to provide some guidance to operations. For example, the use of directional antennas to

eliminate multipaths from behind the antennas should reduce both spatial fading and frequency selectivity. Some form of frequency and polarization dependence is also implied in the model, on the basis of the size, spacing and orientation of the scattering elements of the trees (vertical trunks and somewhat random limbs). For example, the advantage in mean field strength of horizontal polarization over vertical [Jansky & Bailey, 1966] and the larger variations in antenna directivity patterns for vertical polarization suggest that the vertical tree trunks are the more effective scatterers [Hagn, et al., 1966].

The model is not expected to hold at frequencies other than those for which the lateral wave mode of propagation is valid. This frequency range is likely to differ for different environments, but the implications are that the lateral wave holds between about 6 MHz to 100 MHz and becomes less reliable at frequencies above 100 MHz [Sachs, 1966]. At any rate, for frequencies above those for which the lateral wave holds, a total scattering model is intuitively expected to represent the propagation mechanism. Further investigation of the model at the lateral wave frequencies may conceivably lend valuable insight into such an extension to a total scatter model.

Other qualitative inferences may be drawn based upon the scatter model of Figure 5.1, but it seems that further work is required to place the model on adequate quantitative grounds.

## 6. CONCLUSIONS

A dense tropical rain forest is a multipath channel at VHF. The multipath delay spread in such a forest, over relatively smooth terrain, is on the order of  $1 \mu \text{ sec}$  and less, implying a coherent bandwidth on the order of one MHz. Delays of 2 to  $3 \mu \text{ sec}$  were observed only rarely.

The behavior of the peak pulse amplitudes, for pulse modulated VHF carriers, is consistent with earlier established behavior of CW transmissions in the environment: The path loss with range  $d$  increases as  $40 \log d$ , the signal increases with increasing antenna height, the signal is generally stronger for horizontal than vertical polarization and the short spatial signal variations are independent of range.

The pulse amplitude waveforms and spectra are generally distorted within the forested environment, with a pulse amplitude ripple of 10 db and more not uncommon. The distortions are fairly uniformly distributed with range for vertical polarization and somewhat grouped for horizontal polarization. At 50 MHz, the groups of distortions, at horizontal polarization, occurred at the far crests of hills where the mean signal was also relatively low. There was less correlation with terrain at 100 and 150 MHz.

The severity of pulse distortion decreases with increasing receiver antenna height and appears to be independent of transmitter antenna height.

The worst degrees of pulse distortions are obtained at positions of field strength minima for CW transmission. These recur in a quasi-cyclic manner, principally because of standing waves due to backscatter from (presumably) the trees, with spacing between nulls generally being less than one wavelength of the carrier frequency.

Wind-induced foliage motion causes signal variations and is most noticeable at positions of CW minima.

For the receiver located within a clearing, other things being equal, the peak pulse amplitudes are generally, although not always, larger and the pulse distortions greatly reduced relative to those obtained within nearby intervening forest.

For the receiver on a hill, other things being equal, the peak pulse amplitudes are larger and the pulse distortions reduced relative to those obtained nearer the transmitter at the base of the hill.

Extension of the homogeneous slab model to include scattering, wherein the effective scatter is from trees in the vicinity of the antenna terminals, provides a model which is qualitatively consistent with the data thus far available. The scatter model offers insight into the time and frequency selective properties of the forested environment, but more work, both theoretically and experimentally, is required to quantitatively determine the selectivity and refine the model and extend it to greater frequency ranges. Much of this is in progress, but it would also be of interest to investigate the multipath effects for air-to-ground transmissions and in mountainous or rough terrain. Techniques for reducing the multipath effects in these environments, such as directional antennas and diversity schemes, also require further investigation.

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## APPENDIX A

Pulse distortions in a densely forested environment, such as that investigated in this report, are expected, intuitively, to be caused by interference from a number of scattering sources (trees). It is also expected that the number of contributing scatterers varies statistically as the antenna changes locations within the environment. It is practically impossible to visualize all the various ways in which the pulses, arriving via the different paths and having different amplitudes and phases, may combine to yield the received pulse waveform. Some degree of understanding of the multipath effects can be gained, however, by theoretically examining the simple case of two rf pulses interfering with different relative amplitudes and carrier phases. The purpose of this appendix is to present some analytical examples of interference between two such pulses. The intent is simply to aid the reader in visualizing interference between pulses and not to suggest that these simple examples illustrate the entire situation. Similarities between some of the examples here and a number of measured waveforms have been observed, however, and are pointed out below.

Figure A-1 gives theoretical examples of interference between two pulses with a fixed relative delay (delay less than pulse duration), equal amplitudes and various relative carrier phases. This simulates possible two-path situations where the interfering pulses have equal amplitudes.

In Figure A-1, note the similarity between the resultant pulse for carrier phase difference of  $0^\circ$  and the reference waveform of Figure 4.4a. Note also the similarity of the resultant pulses for  $150^\circ$  and  $180^\circ$  phase differences and the severely distorted waveform of Figure 4.4b.

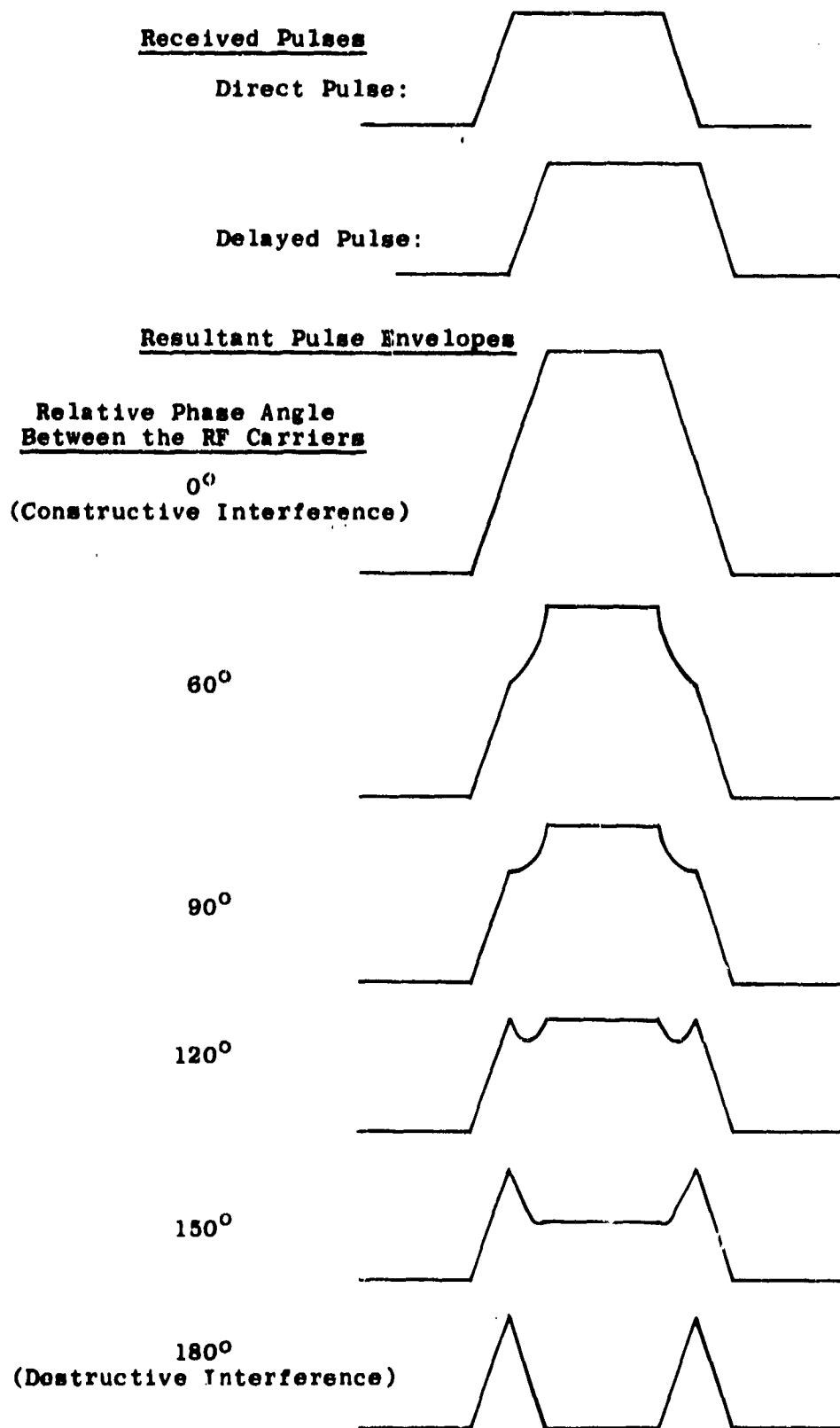


Figure A-1 Theoretical Examples of Resultant Waveforms for Interference Between Two rf Pulses of Equal Amplitude, Fixed Relative Delay, and Various Relative Carrier Phases.

Figure A-2 gives theoretical examples of interference between two pulses with fixed relative delay (delay less than pulse duration), unequal amplitudes and various relative carrier phases. This simulates possible two-path multipath situations where the most direct, or earliest pulse, has the larger magnitude.

In Figure A-2, note the similarity between the resultant pulse, for carrier phase difference of  $0^\circ$ , and the reference waveform of Figure 4.3a. Note also the similarity of the resultant pulses for  $150^\circ$  and  $180^\circ$  phase differences and the moderately distorted waveform of Figure 4.3b.

There were many observations having the similarities pointed out in Figure A-1,2, which suggests that relatively few multipaths may be effective in many instances.

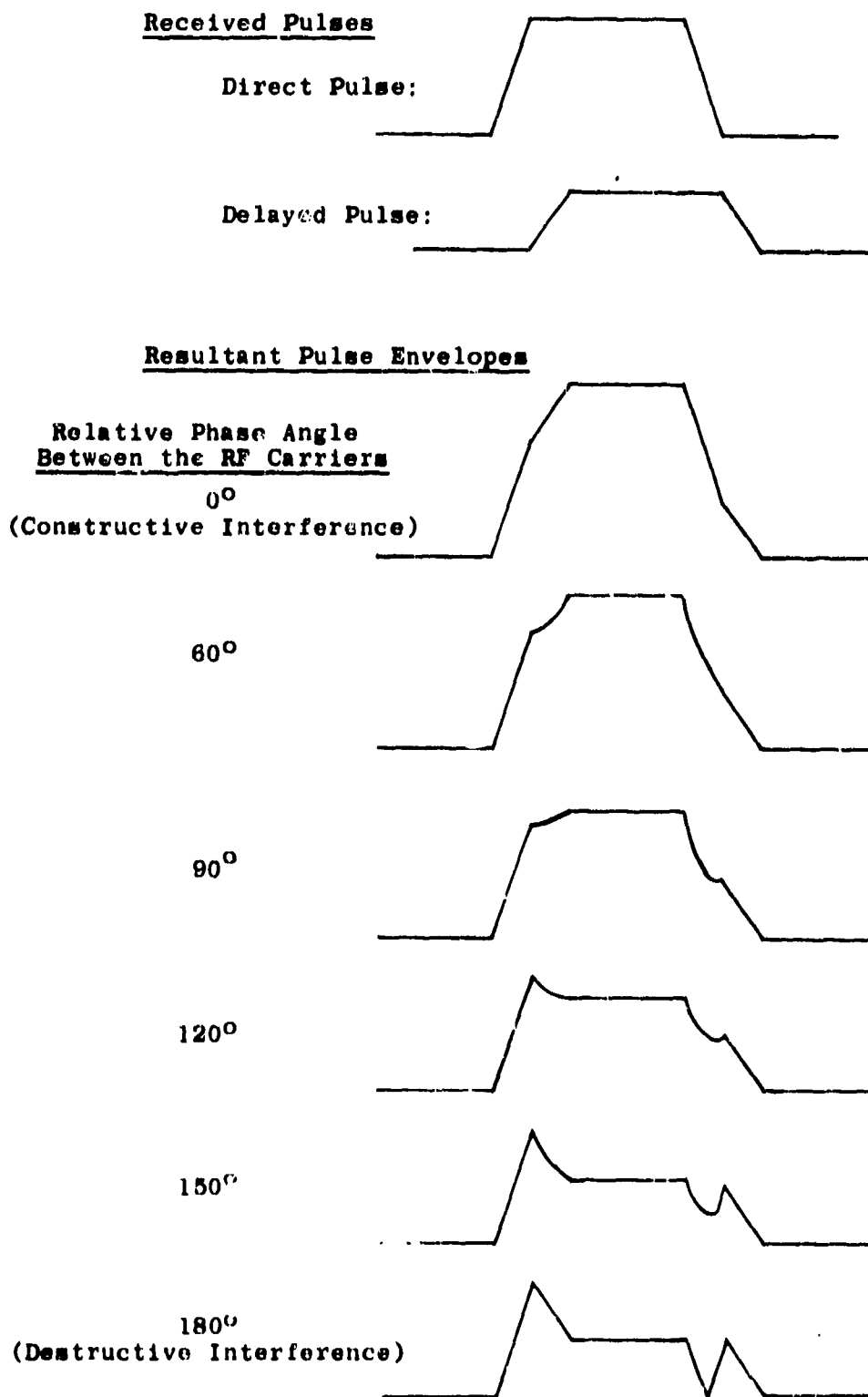


Figure A-2 Theoretical Examples of Resultant Waveforms for Interference Between Two rf Pulses of Different Amplitude, Fixed Relative Delay, and Various Relative Carrier Phases

## APPENDIX B

To demonstrate the cause of quasi-cyclic spatial variations of the signal along a radial from the transmitter, and to gain insight into its behavior, consider interference between two signals of the same frequency, one direct from the transmitter and the other scattered, as in Figure B-1.

Assume that path A, from the transmitter to receiver, and path B, from transmitter to scatterer at point  $(x, y, z)$ , are parallel (as from a distant transmitter) and that path A is along the x-axis. Path C is from scatterer to receiver. The receiver is at the origin of the rectangular coordinate systems.

Let the signal arriving along A have magnitude  $a_0$  at the receiver and the signal arriving along B and C have the magnitude  $a_1$  at the receiver. With the time variation  $e^{i\omega t}$  understood, and zero phase change upon scattering assumed, the field strength  $E_0$  at the receiver is:

$$E_0 = a_0 e^{-ikA} + a_1 e^{-ikB - ik[(x \cos \psi + y \sin \psi) \cos \theta + z \sin \theta]}. \quad (B-1)$$

Referencing the phase to that of path A, for convenience, gives

$$E_0 = a_0 + a_1 e^{-ikx - ik[(x \cos \psi + y \sin \psi) \cos \theta + z \sin \theta]}. \quad (B-2)$$

The magnitude of the field is measured in practice, however, which is

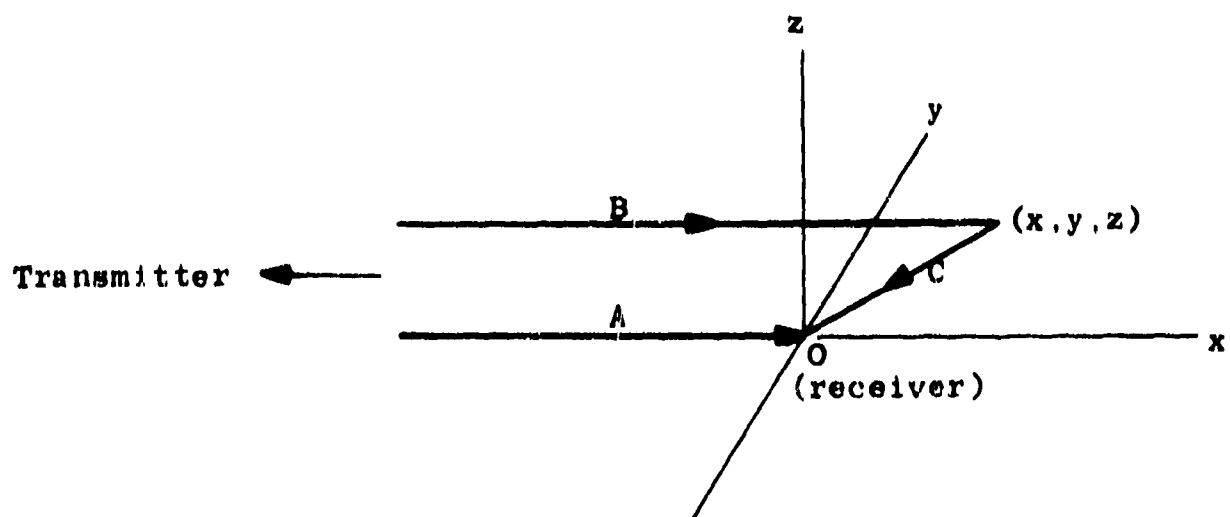


Figure B-1 Sketch of Ray Paths Depicting Scatter and Interference

$$|E_0|^2 = a_0^2 + a_1^2 + 2a_0a_1 \cos k [x(1 + \cos \psi \cos \theta) + y \sin \psi \cos \theta + z \sin \theta]. \quad (B-3)$$

As the receiver is moved along the x-axis,  $|E_0|$  will vary in a quasi-cyclic fashion with spacing between maxima and minima being dependent upon wavelength, through  $k = \frac{2\pi}{\lambda}$ , and location of the scatterer through  $\psi$  and  $\theta$ . A general sketch of the behavior of Equation B-3 is shown in Figure B-2 for constant amplitude signals. To illustrate further the behavior of this equation, if  $\psi = \theta = 0$ ,

$$|E_0|^2 = a_0^2 + a_1^2 + 2a_0a_1 \cos \frac{2\pi}{\lambda}(2x) \quad (B-4)$$

and the spacing between minima, or maxima, is  $\frac{\lambda}{2}$  for  $\theta = \frac{\pi}{2}$ ,  $\psi = 0$

$$|E_0|^2 = a_0^2 + a_1^2 + 2a_0a_1 \cos \frac{2\pi}{\lambda} x \quad (B-5)$$

and the spacing is  $\lambda$ . For  $\theta > \frac{\pi}{2}$ ,  $\psi = 0$ , the spacing is greater than  $\lambda$  and approaches infinity (constant signal) as  $\theta$  approaches  $\pi$ .

As the receiver moves along the x-axis, which is analogous to the measurement procedures along the main access trail, the angles  $\theta$  and  $\psi$  and the amplitudes of the individual signals will, in general, change. Over short distances, however, perhaps a few wavelengths, the relative magnitude of the signals and the angles  $\theta$  and  $\psi$  can probably be assumed constant. If a number of scatterers are considered, the problem may be extended by vectorially summing the individual contributions, with resultant complexities in the standing wave pattern. Further, as the receiver moves, a new set of scatterers are likely to be encountered which may further complicate the standing wave pattern. These may be the causes of the short disruptions observed in the cyclic pattern of CW signal recording [Jansky & Bailey, 1966].

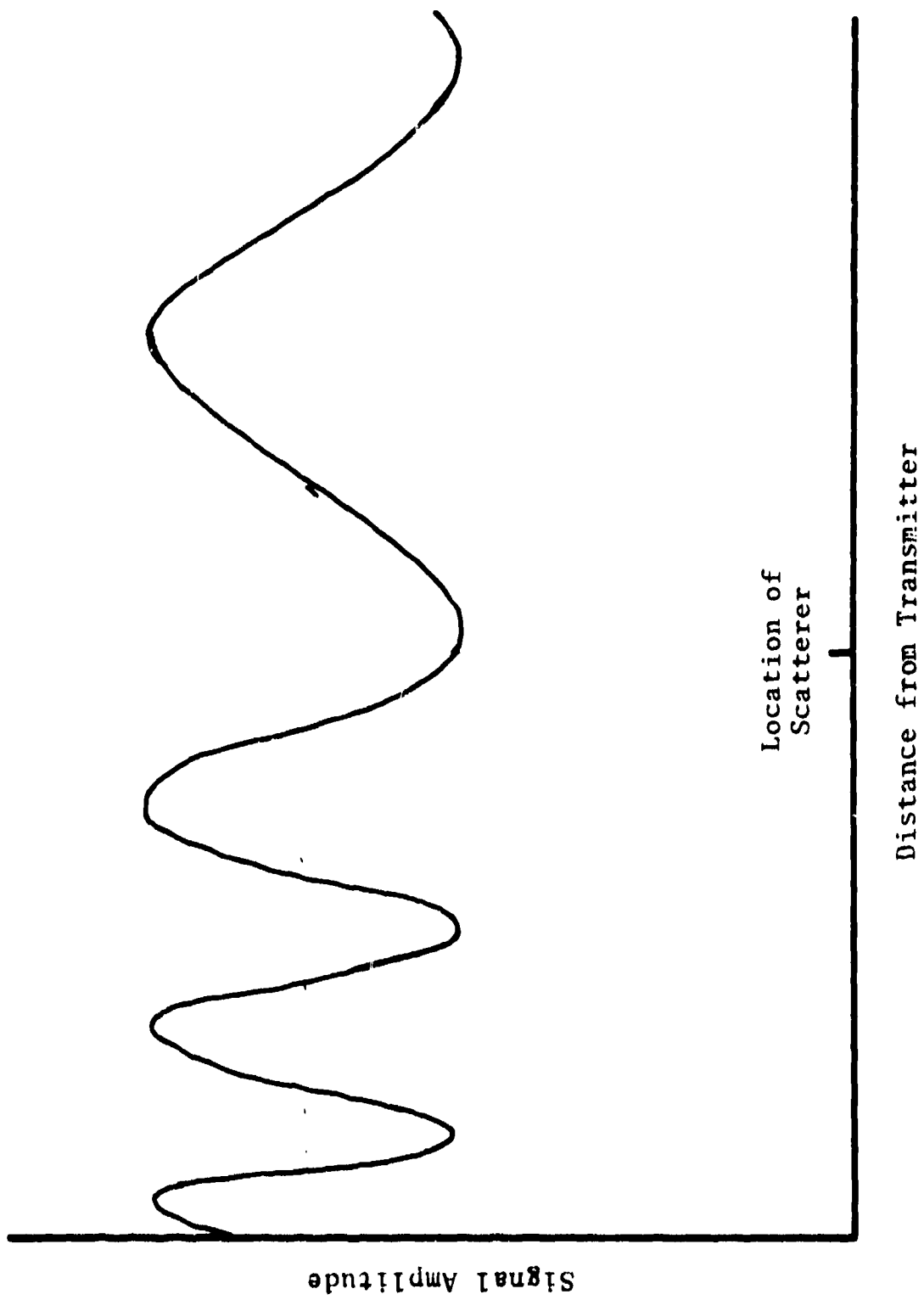


Figure B-2 Sketch of Equation B-3

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13. ABSTRACT <p>This semiannual report is one of a series presenting results from experimental and analytical investigation of the propagation of radio waves in tropical jungle environments. The experimental work has been done in a tropical rain forest test area in Southern Thailand. The objective of this program is to obtain and analyze information that is generally applicable to improving the development, design, and operation of short range communications systems for tropical jungle environments.</p> <p>The work covered by this report is especially concerned with the propagation of pulsed, or digital, signals in such an environment. Transmitted pulses of about 1 <math>\mu</math> sec were received by fixed and mobile receiving systems. Distortion in the pulse amplitude and frequency spectra was measured at carrier frequencies of 50, 100 and 150 MHz. The results of these measurements indicate clearly that the rain forest jungle creates a frequency-selective propagation channel and, with wind-driven tree motion, a time-selective channel as well. The measurements imply a coherent bandwidth of about one MHz for this type of jungle channel.</p> <p>From the data obtained thus far a preliminary model has been constructed, based on multiple scattering from the dominant tree, which qualitatively explains the observed data.</p>			

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